Rapid Decision Support Tool based on Novel Ecosystem Service Variables for Retrofitting Sustainable Drainage Systems in the Presence of Trees

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DECLARATION

In course of this PhD research work, four journal papers were produced from it as listed in the list of publications shown below. Therefore, this report contains parts of the published work including results, discussion, figures and tables.

LIST OF PUBLICATIONS OBTAINED AS A RESULT OF THIS RESEARCH

Journal papers:

1. Scholz, M. and **Uzomah, V. C.** (2013). Rapid decision support tool based on novel ecosystem service variables for retrofitting of permeable pavement systems in the presence of trees. *Journal of Sci. of the Total Environment.* vol. 458. pp. 486-498. My involvement in this paper includes field data collection, analysis of data, and writing up.
2. Scholz, M., **Uzomah, V. C.,** Almuktar, S. A. A. A. N. and Radet-Taligot, J. (2013). Selecting Sustainable Drainage Structures Based on Ecosystem Service Variables Estimated by Different Stakeholder Groups. *Water.* vol. *5,* pp.1741-1759. My involvement in this paper includes field data collection, analysis of data, and writing up.
3. **Uzomah, V.,** Scholz, M. and Almuktar, S. (2014). Rapid expert tool for different professions based on estimated ecosystem variables for retrofitting of drainage systems. *Computers, Environment and Urban Systems*. Vol. 44, pp. 1–14. My involvement in this paper includes field data collection, analysis of data, and writing up.
4. **Uzomah, V. C.,** Scholz, M. & Al-Faraj, F. A. M. (2015). Assessment of tree damage to permeable pavements and other urban structures. *Journal of Sci. of the Total Environment*. (Under review). My involvement in this paper includes field data collection, analysis of the data, production of all tables and most figures, and writing up.

Conference papers:

5. **Uzomah, V. C**. & Scholz, M. (2013) "Rapid decision support tool based on novel ecosystem service variables for retrofitting of permeable pavement systems in the presence of trees". *4th CSE Doctoral School Postgraduate Research Conference: The University of Salford, Manchester.*
6. **Uzomah, V. C.**, Scholz, M. & Sani A. (2013). "Rapid Decision Support Pollution Control Tool Based on Novel Ecosystem Service Variables for Retrofitting of Sustainable Drainage Systems Including Wetlands and Ponds". *14th International Conference on Wetland Systems for Water Pollution Control, China.*

7. Sani, A., Scholz, M., Babatunde, A., Wang, Y. & **Uzomah, V. C.** (2013). "Clogging of Vertical-flow Constructed Wetlands Treating Urban Wastewater". *14th International Conference on Wetland Systems for Water Pollution Control, China.*
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LIST OF ABBREVIATIONS

CIRIA	**-**	**Construction Industry Research and Information Association**
CSO	**-**	**Combined Sewer Overflow**
SUDS	**-**	**Sustainable Urban Drainage Systems**
RPA	**-**	**Root Protection Area**
DBH	**-**	**Diameter at Breast Height (Diameter of a tree trunk at 1.5 m from the ground surface)**
BMP	**-**	**Best Management Practice**
SCM	**-**	**Stormwater Control Measures**
WSUD	**-**	**Water Sensitive Urban Design**
GI	**-**	**Green Infrastructure**
LID	**-**	**Low Impact Development**
SWARD	**-**	**Sustainable Water industry Asset Resource Decisions**
DSP	**-**	**Decision Support Process**
GSDP	**-**	**Glasgow Strategic Drainage Plan**

ABSTRACT

There is a lack of practical decision support tools useful for a rapid assessment of the potential of ecosystem services when retrofitting permeable pavements in urban areas that either feature existing trees or should be planted with trees in the near future. There is also a need for a geospatial decision support tool for different professions such as drainage engineers and urban planners, which is useful for a quick assessment of the potential of ecosystem services when retrofitting sustainable drainage systems (SUDS) in urban areas Therefore the aim is to develop a decision support tool for choosing the best possible options for the retrofitting of sustainable urban drainage system techniques using novel ecosystem service variables and modify it to include a reflection of the confidence level of the assessor to minimise uncertainty, and weighting factors that will reflect the professional background of the stakeholders to reduce professional bias.

This tool was developed and used to assess 100 sites in Greater Manchester with retrofitting potentials including Brownfield sites. The introduced weighting factors helped to narrow down the choices further. Since the retrofitting of SUDS, especially permeable pavements, and other urban development projects usually involve areas where there are already existing mature trees, further studies were carried out on the damage characteristics of urban tree species on urban structures including permeable pavements, impermeable pavements, kerbs, roads and retaining walls. This was conducted on a different 100 sites also in Greater Manchester. Further studies were also carried out about public acceptance of the urban tree species using pictures taken of trees from the Westonbirt National Arboretum.

The results of the 'ecosystem service' approach were compared with those of traditional 'community and environmental' approach developed by CIRIA. A comparison with the traditional approach of determining community and environment variables indicates that permeable pavements are generally a preferred SUDS option regardless of the professional perspectives. The introduced weighting factors made the tool lend itself to be used by stakeholders of varying professional backgrounds. The results of the comparison of the different approaches showed that the 'ecosystem service' approach gave a rather more thorough and precise assessment and will give a less misleading choice of SUDS techniques. In comparison to common public opinion, statistically significant differences between social scientists and the general public for the estimation of *land costs* using the non-parametric Mann-Whitney U-test were found. It was also surprising to find no significant differences in the estimation of *habitat for species* by civil engineers and ecologists. Permeable pavements combined with urban trees received relatively high scores, because of their great potential impact in terms of water and air quality improvement, and flood control, respectively.

The result of the assessment of damages to structures by urban tree species revealed that Norway maple, Lime, Common Ash and Sycamore dominated Greater Manchester, and showed that certain tree species are better suited for certain structures either because of the damage or the nuisance that the trees cause. Impermeable pavements were subject to the highest number of damage from trees (44%), followed by permeable pavements and kerbs (22% and 19%, respectively). Trees planted close to impermeable pavements will cause more damage to the structure compared to those planted close to permeable pavements under the same conditions. Wild cherry, large leaved lime, horse chestnut and hawthorn may are the best recommended trees for use alongside most roads and SUDS structures as they have least potential to damage structures. However, horse chestnuts produce lots of litters with their conkers. From aesthetics point of view, sycamore was the most aesthetic tree all-round the year.

This study therefore suggests best tree species for permeable pavements and other related structures, and its outcomes are likely to lead to more combined permeable pavement and tree systems in the urban landscape, which are beneficial for humans and the environment. It will help urban developers in choosing the most suitable trees for the right urban environment. It will also help to save money in maintaining infrastructure such as roads and pavements.

Keywords: Sustainable urban drainage systems; Ecosystem services; Permeable pavements; Expert system; Different professions; Stakeholders; Uncertainty; Urban trees; Urban structures, Structural damage.

CHAPTER 1

INTRODUCTION

1.1.Background

Increasing urbanization is causing problems such as increased flash flooding after sudden rain. As areas of vegetation are being replaced by impermeable concrete, tarmac and roofed areas, the area loses its ability to absorb rain water. The large scale flooding in many parts of the country during the summer of 2007 greatly affected the lives of many people and caused an estimated £3 billion worth of damage to property (Defra, 2012). In August 2008, the Greater Belfast Area and parts of Antrim were affected by flooding. The Cumbria floods in 2009 resulted in £100s millions of damage, including the loss of twenty road bridges and long term disruption for local communities (Defra, 2012). Over the past few years the UK has been affected by increasing run of severe winter and summer storms and resulting in widespread flooding across the country – the latest being the significant UK flood events of winter 2013/2014 (RIBA, 2014). The clear-up costs of the last winter floods alone cost £1bn, with smaller firms losing £830m and insured losses up to £1.5bn (RIBA, 2014). The impacts of the increasingly intense downpours driven by climate change, as well as population growth and urbanisation, will see the cost of flood damage cost rise fivefold in the UK by 2050, up to £23bn a year (Jongman et al., 2014). The Water Services Regulation Authority estimates that about half the average annual flooding incidents (between 5,000 and 7,000) are as a result of the capacity of the drainage system being exceeded (Environmental Agency, 2007). It has been estimated that these flooding events will continue to increase as human population and infrastructures increase (Defra, 2012).

A sustainable drainage system (SUDS) is designed to reduce the potential impact of new and existing construction developments with respect to surface water drainage discharges. The use of SUDS is a good eco-innovation application. However, challenges include the need for large areas of land required for retrofitting SUDS in urban areas. Urban vegetation such as mature trees could be integrated into new SUDS schemes to reduce and attenuate run-off, making them more efficient and reduce space requirements.

Traditional drainage often creates flooding and pollution problems in the lower catchment (CIRIA, 2007; Scholz et. al., 2006). The implementation of sustainable drainage systems (SUDS) can help to reduce these problems (CIRIA, 2007). Sustainable drainage systems (SUDS) concept is to mimic, as closely as possible, natural drainage of a site in order to minimise the impact that urban development has on flooding and pollution of rivers, streams and other water bodies (CIRIA, 2004). SUDS techniques include: permeable pavements, filter strips, swales, green roofs, ponds, constructed wetlands, infiltration trenches, soakaways, infiltration basins, belowground storage, and water playgrounds. The use of a variety of these techniques within the management train allows the SUDS concept to be applied to all sites. The techniques that utilise vegetative features to treat pollution and slow down or reduce flows can also be used to enhance the landscape and at the same time provide wildlife habitat.

Sustainable drainage techniques should be able to reduce the impact of urbanisation on the quantity and quality of surface runoff, while increasing amenity and biodiversity opportunities at the same time. Some of the techniques control surface runoff through infiltration, detention, attenuation, conveyance and water harvesting (CIRIA, 2007; Scholz et. al., 2006; Scholz et al., 2012). In general, they make use of physical, chemical and/or biodegradation processes to improve the quality of surface runoff by minimising the amount of storm water-based pollutants washed into nearby watercourses

Erickson et al., 2007; Scholz, 2010). However, improvement opportunities with respect to ecosystems services including amenity and biodiversity by introducing SUDS are frequently ignored by engineers (Scholz, 2010).

One of the requirements of the National Standards for Sustainable Drainage Systems is that surface runoff is managed at its source where it is reasonably practicable to do so (Defra, 2011). The concept of 'source control' for the treatment of stormwater runoff from impervious surfaces has become widely accepted among drainage engineers in both the United States and Europe (Ellis et. al. 2004; Scholz 2006; Scholz 2007). Over the past 20 years, the use of best management practice, BMP (more recently stormwater control measures, SCM) in the United States and sustainable urban drainage systems (SUDS) in the United Kingdom have been instrumental in reducing both the detrimental impact of the polluted runoff to the water quality of receiving water courses, and flooding caused by increased urbanisation and traditional stomwater drainage systems (Scholz, 2007). However, because of the importance of SUDS in the stormwater management, a multitude of new terms have consequently emerged for it which includes Stormwater Best Management Practices (BMPs), Green Infrastructure (GI), Low Impact Development (LID), and Water Sensitive Urban Design (WSUD) (Lerer, et. al., 2015).

The Ecosystem service approach is a technique, strategy or practice for the integrated management of land, water and living resources that promotes conservation and sustainable use in a justifiable way (Scholz, 2010). The increasing human population size, economic growth and global consumption patterns place pressure on environmental systems; thus the provisioning of ecosystem goods and services is affected (Seppelt et al. 2011). There is therefore increasing public awareness of the importance of ecosystems and the services they provide for humans (Butler & Davies, 2004; Scholz, 2010). The concept of ecosystems services has become an important model for linking the functioning of ecosystems to human welfare. Understanding this link is critical for a wide-range of decision-making contexts (Fisher et. al., 2009). Adequate consideration of ecosystem services in the choice and design of engineering structures is therefore very important.

Urban trees reduce stormwater runoff, reduce air temperatures (Sitawati, et. al., 2011; Nowak, 2010; Nowak et. al., 2013; Leuzinger, 2010), remove pollutants (Becket et. al., 2000), and provide ecosystem services including amenities. Urban trees also improve human wellbeing, purify the air and increase house prices and aesthetic value of a place. Unfortunately, urbanisation has resulted in the loss of large numbers of mature forest trees on the rural urban-fringe (Volder et al., 2009). There is a growing body of research that supports the importance of maintaining healthy and sustainable urban trees. Many local authorities and organisations embark on tree planting campaigns and encourage street tree planting for its varied advantages. On the other hand, trees can also cause various kinds of damage to urban structures such as: permeable pavements, impermeable pavements, kerbs, roads, footpaths, buildings and retaining walls. Recent experiences have shown that, the planting of street trees with all good intention is not sufficient to achieve a high quality streetscape. To achieve successful streetscapes critical factors such as selection of the most appropriate and cost-effective tree species, quality of the corresponding plant stock and planning for and providing adequate soil and water are essential (Mather and Morton, 2008). There is therefore, an urgent need to consider appropriate tree selections in the engineering design of urban structures and areas.

Research also shows that cities are spending substantial sums of money to address conflicts between street tree roots and urban infrastructure (Randrup, et.al., 2003), and most of these expenditures are wasted on dealing with problems that already exist. It will make more sense if part of this money is spent in minimizing the future occurrence of these conflicts by studying the relationships between the damage from roots with the corresponding tree species, tree characteristics, soil characteristics and the design of infrastructure. An assessment of this sort becomes important as part of a decision support tool for the fitting and retrofitting of sustainable urban drainage systems (SUDS), and in the planning of tree planting projects at urban development sites, regeneration projects, and sustainable drainage projects (Scholz and Uzomah, 2013).

1.2. The Need to Involve Different Professions in Planning for SUDS

A truly trans-disciplinary collaboration is required to build a balanced assessment method for supporting multi-functional SUDS design aimed at improving the life quality of urban systems. A SUDS design team should be multi-disciplinary and have: (i) a strong landscape and urban design influence to guide the form and shape of the SUDS, especially in the early stages of the development design; (ii) drainage engineers with the expertise to ensure the proposed design will provide effective drainage; and (iii) ecologists providing advice on how to improve the biodiversity. It is important that an effective SUDS team will work through these issues right from the early stage in the scheme development.

In addition to the above professions, others that could be involved in the design, construction and future maintenance of any adoptable SUDS include: Developers, Engineers, Landscape designers, Architects & urban designers, Development control and other City Council officers, and City Council maintenance team (Anglian Water, 2014). The essence of involving these professionals right from the early stage of the scheme is so that they would find the most appropriate way to identify and deal with any conflicting design aims. Many researchers (Ashley et al., 2008; Babbs, 2011; Maslen Environmental, 2011; and Digman et al., 2012) have recognized the benefits of establishing partnerships and having different stakeholders work together and concluded that it can also reduce cost of SUDS retrofitting. Barbosa et. al. (2012) concluded that Best Management Practices (or SUDS) can be seen as an opportunity for development and improvement of social, educational and environmental conditions in urbanized and surrounding areas, they should, therefore, require an ample perspective and the participation of different stakeholders. In retrofit schemes, CIRIA (2015) recognised that stakeholder engagement right from the early stage can facilitate potential partnership funding opportunities, which in turn can also help with securing the most cost-effective and highest quality schemes. Balmforth et. al (2006) stressed that the achievement of good exceedance design will be possible through effective stakeholder involvement, interaction and dialogue, which includes stakeholders with drainage interests, planners, developers, local interest groups and homeowners.

1.3. Justification, Aim and Objectives

Established tools evaluating a range of SUDS techniques for retrofitting of drainage systems already exist (e.g., CIRIA, 2004). However, sophisticated tools focusing on the retrofitting of SUDS including permeable pavements on sites with existing trees and taking into account a wide range of ecosystem service variables (including functions associated with trees) do not exist. CIRIA (2004), and Scholz et al., (2006) have tried to come up with decision support models for the selection of SUDS techniques. However, CIRIA model did not consider detailed ecosystem services. Both CIRIA (2004) and Scholz et al., (2006) did not consider the perspectives of different professionals, the uncertainty in estimations, and the effects of existing trees on SUDS sites.

More so, among the existing decision support tools for retrofitting SUDS, no consideration has been made of the importance of producing a decision support tool that: is cheap and simple to use, is easily adaptable for different stakeholders involved with SUDS irrespective of their professional background, considers the confidence of the assessors in each of the assigned values, uses detailed ecosystem services that will adequately reflect the need for the environment, the human wellbeing and other associated organisms.

In times of recession and spending cuts in the public sector, rapid and inexpensive expert assessment systems supporting SUDS planners become very necessary, and currently undergoing a revival in the context of ecosystem services. The application of ecosystem service values to a new area such as sustainable drainage is a novel contribution to knowledge and understanding. The timely and applied nature of such expert systems should have a strong appeal particularly for urban and landscape planners interested in the total environment.

Estimating rather than measuring complex ecosystem service variables reduces the overall cost and length of a project considerably. Euliss et al. (2011) showed the successful integration of estimated ecosystem service variables within models used for decision-support process. There is therefore a need to develop a SUDS retrofitting decision support tool that will be cheap, robust, and can be adapted to be used by different professions without introducing much professional bias. In addition, considering the contribution of trees to human wellbeing and the need to include tree planting in development plans, there is a need to study tree species characteristics and their impacts on permeable pavements and other structures. It is therefore needful to consider the best urban tree/urban structures combinations in the decision for retrofitting of sustainable drainage system techniques and other urban structures.

The aim of this research is to develop a unique and rapid decision support tool based on novel ecosystem service variables for retrofitting of sustainable drainage systems and other urban structures in combination with tree systems in densely populated areas. Such tool should also be able to lend itself to the perspectives of the different professional backgrounds of SUDS stakeholders. The key objectives to achieve this aim are to:

- develop and modify a data collection tool for site assessment towards SUDS retrofitting, aiming to reduce uncertainty in estimation (Appendix A);
- compile a comprehensive dataset of sites within an example case study area (Greater Manchester) where retrofitting of SUDS would be possible (Chapter 4);
- broadly categorise all identified generic ecosystem service variables relevant for SUDS retrofitting under the four established categories of supporting, regulating, provisioning and cultural (Table 3.1, 3.2, and 3.3);
- assess and compare the suitability of potential SUDS sites within Greater Manchester based on the traditional 'community and environment' variables, the new ecosystem service variables and a combination of the traditional and new approach for sites within Greater Manchester, and their suitability for assessing the retrofitting option of the SUDS techniques including the combined permeable pavement and tree system (Chapter 4);
- introduce a weighting system into the decision support tool (for SUDS retrofitting) taking into account the perspectives of drainage engineers, developers, ecologists, planners and social scientists to reduce professional bias, so that the tool can become adaptable for use by various professionals (Table 3.4, Section 3.3 and chapter 5);
- identify the predominant trees in Greater Manchester and assess their public acceptance using similar tree species from The National Arboretum at Westonbirt (sections 3.2.8 and 3.5);
- randomly select representative sites in Greater Manchester to study the tree damage characteristics (Figure 3.6, section 3.4 and chapter 6);

- collect comprehensive dataset of tree characteristics, including tree locations, height, diameter at breast height (DBH), crown spread, distance from structures, for species found close to structures (section 3.4);
- analyse the damage caused by urban tree roots in relation to tree characteristics such as species, distance from structures and DBH (chapter 6).
- assess the damage characteristics of each predominant tree species with respect to structures such as permeable pavements, impermeable pavements, roads, kerbs, footpaths, and retention walls (chapter 6).
- identify trees species that may impact on the retrofitting of permeable pavement systems and other related urban structures (chapter 6).

1.4. Thesis Outline

Chapter 1 presents the background information for this research work, the need to involve different stakeholder with their different professional background in the planning of SUDS and this forms the basis for introducing weighting systems for different professions in this research. This chapter also gives the justification for the research work, and the aim and objectives.

Chapter 2 presents literature review of existing publications on SUDS, retrofitting of SUDS techniques, benefits of using SUDS, ecosystem services, tree species, benefits of urban trees, damage caused by urban trees. Chapter 2 also compares the natural and urban catchments in view of their hydrological processes and then reviewed the efforts made by some researcher in coming up with retrofitting decision support tools, and compared them.

Chapter 3 gives the methodology of the research. The work was carried out in three parts: part 1 describes the incorporation of ecosystem service variables into the developed SUDS decision support tool, and how it was used to assess 100 potential SUDS retrofitting sites in Greater Manchester, and how comparison was made of the three assessment approaches; part 2 describes how weights were incorporated into the tool to reflect the perspectives of the different professional backgrounds of the stakeholders; part 3 describes how assessment was carried out of the different urban tree species and their damaging characteristics in relation to urban structures, it also describes how public perception of prevalent urban trees were carried out.

Chapter 4 discusses the result of using the developed tool to assess the retrofitting options of 100 potential retrofitting sites in Greater Manchester. Results of using the three approaches were also discussed and compared.

Chapter 5 discusses the result of allocating weighting systems to the assessed data with respect to the different professions expected of a stakeholder. Professions such as Drainage Engineers, Developers, Ecologists, Planners and Social Scientists were assigned weights based on the results of the public assessments of representative sites.

Chapter 6 discusses the results of the assessment of the damage characteristics of some urban tree species on some urban structures. It also shows the analysis of the percentage of structural damage based on tree 'diameter at breast height' (DBH) and distance of trees from structures.

Chapter 7 presents conclusion of the research and recommendations for further research. Appendix is also added after this chapter.

CHAPTER 2

LITERATURE REVIEW

This research work has led to the publication of four journal papers, and as such, some of the contents of this chapter, including tables and figures may have been used also in one or more of the publications, as listed on page xiii.

2.1. Need to rethink the philosophy of drainage systems

Traditionally, combined sewer systems are used to deal with wastewater and storm water runoff. These sewerage systems operate on the philosophy of preventing local flooding by conveying surface runoff away as quickly as possible. Combined sewers function by carrying both wastewater and storm water in a single pipeline to a wastewater treatment plant, where it is treated and discharged into a suitable natural watercourse such as a river (Scholz, 2006). During periods of medium or heavy rainfall, when sewers are incapable of carrying an increased flow, a structure called the combined sewer overflow discharges untreated wastewater directly into natural watercourses to relieve combined sewers from high runoff loads (Butler and Davies, 2011; Scholz, 2006, 2010).

Separate sewer systems are nowadays being designed to reduce the pressure caused by medium and heavy rainfall, by carrying surface runoff and wastewater in separate pipes. Surface runoff is conveyed in a dedicated pipe and discharged straight into a watercourse without being treated (Butler and Davies, 2011). This more modern sewerage system is advantageous over the combined sewer system, as it does not discharge wastewater directly into receiving watercourses. However, the untreated surface runoff still contains some unwanted contaminants from urban services (CIRIA, 2007; Scholz, 2006, 2010).

Traditional drainage often creates flooding and pollution problems in the lower catchment. The implementation of sustainable drainage systems (SUDS), also known as best management practices, can help to alleviate these problems. The philosophy of SUDS is to mimic the natural drainage into the ground, as closely as possible, prior to its development (CIRIA, 2007). Most SUDS techniques are able to do this in number of ways such as attenuation of runoff before entering the watercourse, storage of water in natural contours, infiltration of partially treated runoff into the ground and evapotranspiration of surface water by vegetation (CIRIA, 2010; Scholz, 2010).

The main objective of SUDS is to reduce the negative impact of urbanisation on the quantity and quality of surface runoff, while simultaneously increasing amenity and biodiversity opportunities, where possible. SUDS are capable of managing and controlling surface runoff through techniques such as infiltration, detention/attenuation, conveyance and/or rain harvesting (CIRIA, 2007; Scholz et al., 2006). In general, they make use of physical, chemical, and/or biodegradation processes to improve the quality of surface runoff by minimising the amount of storm water-based pollutants washed into nearby watercourses (Eriksson et al., 2007; Scholz, 2010). However, potential improvement opportunities in terms of ecosystem services including amenity and biodiversity by introducing SUDS are often neglected by engineers and planners in practice.

2.2. Sustainable Urban Drainage Systems (SUDS)

Sustainable Urban Drainage System (SUDS) mimic natural drainage patterns by: storing runoff and releasing it slowly (attenuation); allowing water to soak into the ground (infiltration); filtering out pollutants; allowing sediments to settle out by controlling the flow of the water; creating attractive environments for people and wildlife (CIRIA (C687), 2010).

2.2.1. Natural and urban catchments

SUDS try to bridge the gap between natural and urban catchments. In natural catchments, there are slow surface water runoff, higher infiltration into the ground, higher evapotranspiration from vegetation and surface water, and higher groundwater recharge, while in urban catchment, there are rapid surface water runoff, limited infiltration into the ground, reduced evapotranspiration from vegetation and surface water, and reduced groundwater recharge (see Fig. 2.1). The differences between the natural and urban catchments widen as more areas are developed. These differences, if unchecked will cause flooding in urban areas during peak precipitation.

Originally channels, drains and sewers could accommodate the surface water runoff for all but the most extreme rain events, while the water courses continued to drain the underdeveloped areas that were left. But as cities expanded rapidly, sewers quickly became overloaded and many watercourses were culverted to create even more space to build on (Digman et. al., 2012). It was soon realised that investments in increasing sewage capacity could not keep pace with urban growth. Sewer overflows were constructed to provide relief, but as many sewers conveyed foul sewage, these overflows caused pollution to receiving waters (Butler and Davies, 2011).

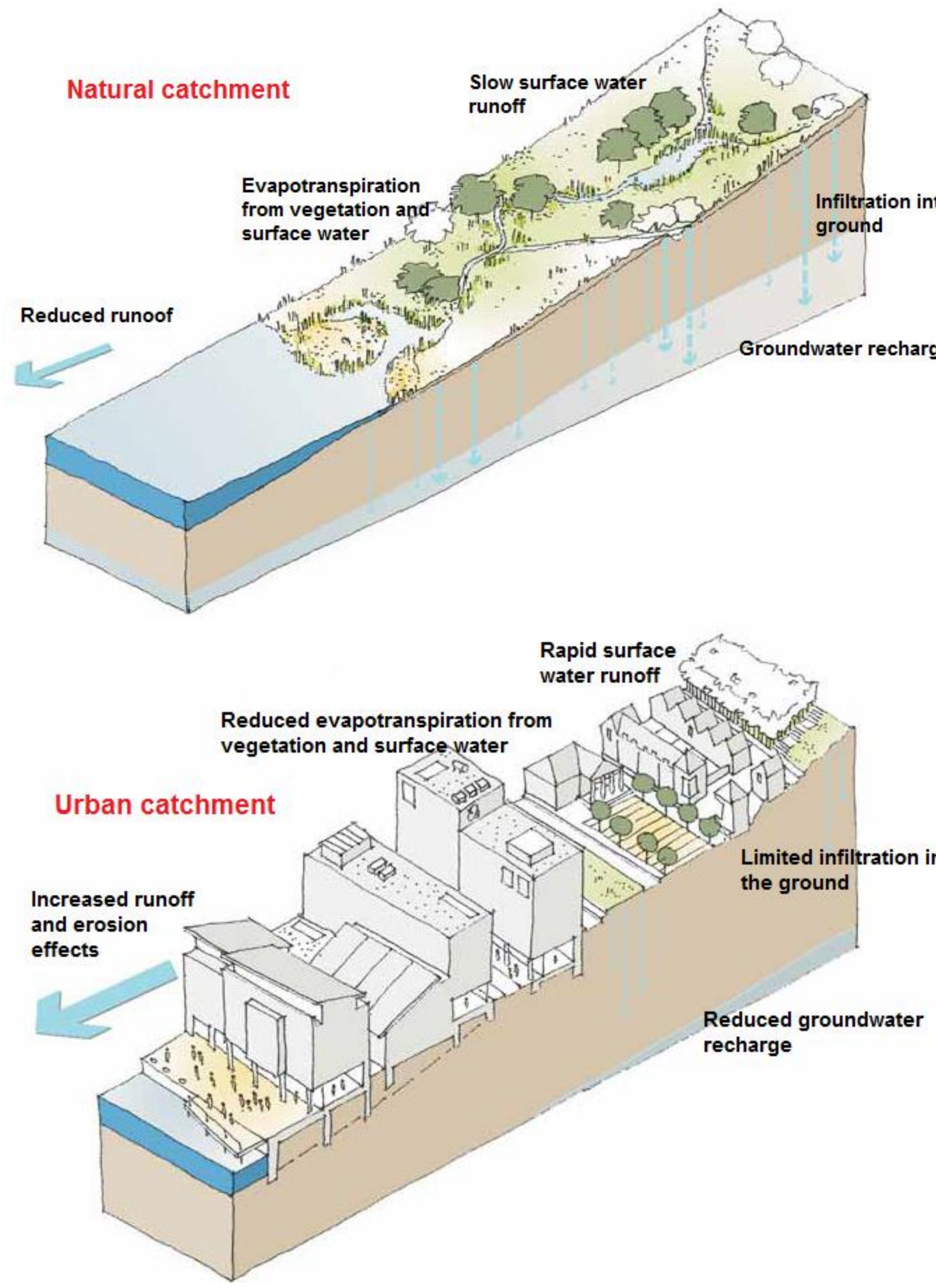


Fig. 2.1: Pre- and post-development hydrological process. (Adapted from CIRIA,2010).

Urbanization produces numerous changes in the natural environment it replaces (Jacobson, 2011). These changes are increasing, and it is predicted to rise from 75% of people in developed countries in 2000 to 83% in 2030, while over the same period it will rise from 40% to 56% in less developed countries (Cohen, 2003).

Gupta and Nair (2011) listed some of the major hydrological effects of urbanization as: (1) increased water demand, often exceeding the available natural resources; (2) increased wastewater, burdening rivers and lakes and endangering the ecology; (3) increased peak flow; (4) reduced infiltration and (5) reduced groundwater recharge, increased use of groundwater, and diminishing base flow of streams. Urbanization has marked effects on basin run-off in terms of higher volume, higher peak discharge, and shorter time of concentration.

Apart from hydrological changes, urbanisation also causes increased sediments and pollutants concentrations down the receiving water courses. Owens and Walling (2002) reported that the total phosphorous contents of sediments in rural and urban catchments increased with increasing levels of urbanization, and Bay et al. (2003) reported that differences in the level of urbanization in differing watersheds were likely to be responsible for the differences in toxicity in stormwater plumes.

Surface water drainage from developed areas is increasingly affecting our river catchments. As development intensifies, so more water runs rapidly into rivers and less percolates through the soil. This sealing of the ground can and does lead to localised flooding and water pollution, and will only get worse as our climate changes (Environment Agency 2003). We therefore need a new approach to drainage that can keep water on site longer, prevent pollution and allow for storage and use of the water. Many existing drainage systems are damaging the environment and are not, therefore, sustainable in the long term. Techniques to reduce these effects have been developed and are collectively referred to as Sustainable Drainage Systems/Sustainable Urban Drainage Systems (SUDS).

2.2.2. Climate change

Key predicted climate change effects include: general warming; hotter, drier summers; warmer, wetter winters; greater variability in year-to-year precipitation; changes in the number of intensive rainfall events; and associated changes in soil moisture and the length of the thermal growing season (Avery, 2012).

Our climate is changing, and recent research suggests that: winters may become milder and wetter with more intense rainfall events; summers may be hotter and drier across the UK; extreme weather events may become more frequent, e.g. heat waves, cold snaps and heavy rainfall (CIRIA, 2010). As the risk of flooding increases with climate change, so also should the capacity of the major drainage systems. Therefore, we need to have drainage systems that can adapt to and manage the extreme events of flooding, while reducing our carbon emissions.

Climate change will put additional stresses on aging water infrastructure with increased temperatures and changes in precipitation patterns, leading to more extreme events such as flooding and drought (IPCC 2012). Changes in precipitation patterns may increase the amount of localized flooding; making it important to consider land-use planning to mitigate these potential impacts (Whitler and Warner, 2014).

2.3. Planning for SUDS

2.3.1. SUDS Design Criteria

SUDS are designed to meet some criteria which comprise the requirements for the elements of the SUDS philosophy: Quantity and Quality with Amenity and Biodiversity as in Fig. 2.2.

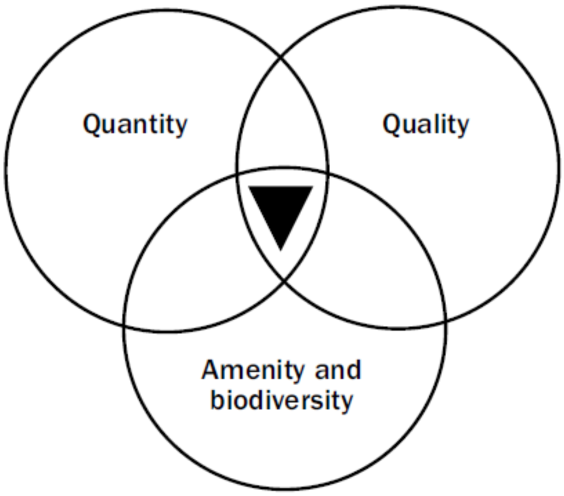


Fig. 2.2: SUDS design criteria. (Source: CIRIA, 2007)

2.3.1.1. Quantity

SUDS reduce the risk of flooding and erosion by controlling flow volumes and the frequency of surface water runoff. Any SUDS design should demonstrate that the Hydraulic Criteria set out in The SUDS Manual CIRIA C697 section 3.2 (CIRIA, 2007) and the requirements of the Environment Agency and the Internal Drainage Board have been considered and incorporated in the SUDS design. Such criteria should ensure that: (i) people and property on the site are protected from flooding; and (ii) the impact of the development does not worsen or impair flood risk at any other point (either upstream or downstream) in the catchment of the receiving watercourse.

2.3.1.2. Quality

SUDS should be able to prevent and treat pollution in surface water runoff to protect the environment. The SUDS design should therefore demonstrate that the Water Quality Criteria set out in The SUDS Manual CIRIA C697 section 3.3 (CIRIA, 2007) and the requirements of the Environment Agency or Internal Drainage Board have been considered and incorporated in the SUDS design. Such criteria include: implementing an appropriate management "train" of SUDS components to effectively reduce the pollution risks associated with different site activities.

2.3.1.3. Amenity

SUDS should also provide visual and community benefits for people. The SUDS design will demonstrate that the Amenity Criteria set out in The SUDS Manual CIRIA C697 section 3.4 (CIRIA, 2007) and any requirements of the Local Authority have been considered and incorporated in the SUDS design. Such criteria include: (i) Health and safety, (ii) Visual impact, and (iii) Amenity benefit.

2.3.1.4. Biodiversity

SUDS should enhance and create ecological diversity and wildlife. The SUDS design will demonstrate that the Ecology Criteria set out in The SUDS Manual CIRIA C697 section 3.5 (CIRIA, 2007) and any requirements of the Local Authority have been considered and incorporated in the SUDS design. Such criteria include: (i) Using native planting; (ii) Locating the SUDS in or near an area where the landscapes are not yet intensively managed, e.g. close to natural pond and wetland habitats; (iii) Retaining and enhancing natural drainage systems (e.g. infiltration); (iv) Creating a range of habitats; (v) Including a shallow, aquatic bench in pond designs; and (vi) Putting in practice an appropriate maintenance and management plan.

2.4. Benefits of SUDS

Darlow et al., (2003) stated that the multi-functional benefits of SUDS can be maximised by adopting an integrated approach to planning by groups such as local planning authorities, water service providers, environmental regulators, engineering consultants and NGO's. They concluded that a holistic approach to the management of surface water which includes SUDS and their associated watercourses can provide significant environmental gains. Fig. 2.3 presents the various benefits of SUDS.

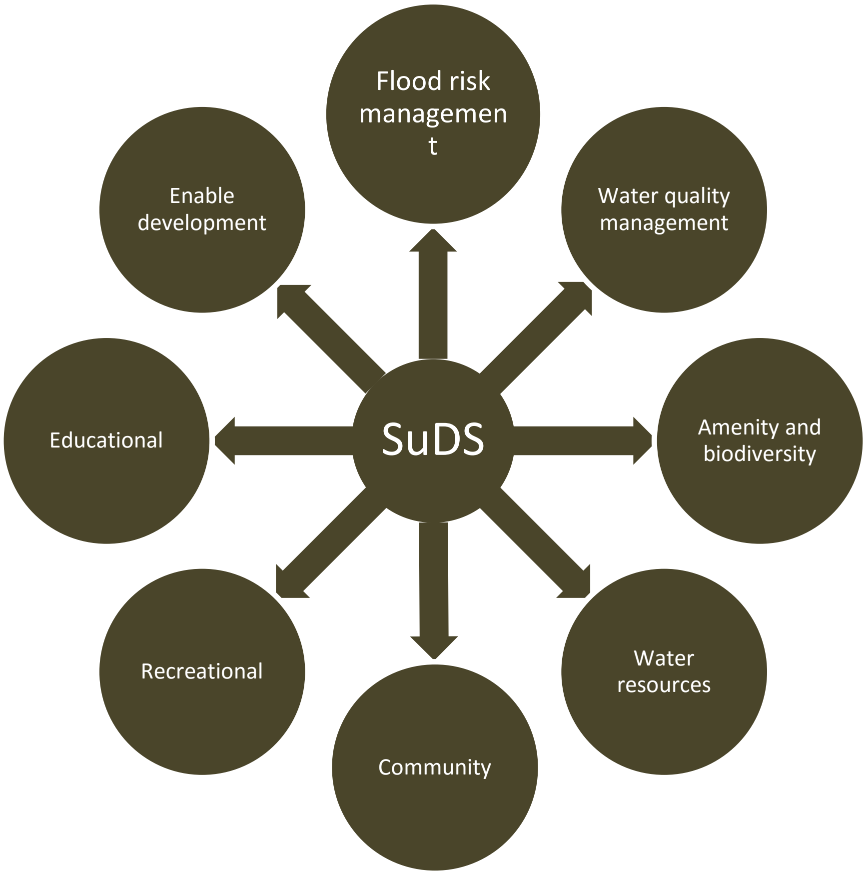


Fig. 2.3: SUDS benefits (Adapted from CIRIA, 2010).

Many researchers have considered the benefits of SUDS in terms of the following categories, which are not mutually exclusive but can overlap and reinforce one another (CIRIA, 2013):

1. Direct economic value – e.g. increase in land value and decrease in house insurance policies due to flood reduction; increase in fisheries production, etc. due to pollution control (e.g. Penning-Rowsell et al, 2005; Kenny et al., 2006).

2. Increase in aesthetic and amenity value due to additional green space (e.g. Natural England, 2009; 2013)

3. Increase in environmental or ecosystem value due to less stress on the environment or the emergence of new biodiversity in urban areas – which relates to ecosystem services (Sukhdev et al, 2010).

4. Diversification of social benefits which tend to be less easily quantifiable (SROI, 2012)

2.4.1. Flood Risk Management

Sustainable drainage involves managing rainwater (including snow and other forms of precipitation) with the aim of:

(a) Reducing damage from flooding

(b) Improving water quality,

(c) Protecting and improving the environment,

(d) Protecting health and safety, and

(e) Ensuring the stability and durability of drainage systems (HMSO, 2010).

The effects of climate change will continue as extreme weather events and global warming become more apparent. In recent years the UK has seen an increase in the number of flood events and flood risk warnings in many areas. Approaches to limiting disruption and damage from flooding are changing significantly from a strategy of flood defence to one of flood risk management using combinations of sustainable drainage system techniques (Defra, 2014).

The strategies for Natural Flood Management rely on one, or a combination, of the following fundamental mechanisms:

- Storing water through the use of ponds, ditches, embanked reservoirs, channels or land;
- Increasing soil infiltration, thereby reducing surface runoff (Defra, 2008), although this can be counterbalanced by greater subsurface flows. Free-

draining soil will make saturation less likely, and evaporation from soil will make space for more water to infiltrate;

- Slowing down water speed by increasing resistance to its flow, for example, by planting shrubs, grasses or riverside woods;
- Limiting joining-together of water flows by interrupting surface flows of water, for example, by water storage or planting buffer strips of grass or trees.

2.4.2. Water Quality Management.

Human activities usually lead to producing numerous pollutants (such as sediments, litter, pesticides, fertilizers, oil, animal waste, and other forms of chemicals) which can easily cause diffuse pollution and can adversely affect the environment. Traditional piped drainage systems are not built to manage these forms of pollutants, and therefore they are washed into sewers and eventually watercourses in surface water runoff, making it difficult to comply with water quality legislation (CIRIA, 2010; Freni et al., 2010).

Some SUDS techniques, such as permeable pavements, filter drains, bio-retention, swales, ponds, wetlands, etc., provide water quality improvements by reducing sediments and contaminants from runoff either through settlement or biological breakdown of pollutants (D'Arcy and Frost, 2001; CIRIA, 2010; Segaran et al., 2014.

2.4.3. Amenity and biodiversity.

Some SUDS techniques such as wetland and pond systems are primarily constructed for improving water quality and reducing the quantity of run-off to receiving watercourses. However, they also have the potential to contribute value in terms of amenity and biodiversity in urban areas (Briers, 2013). In general, it has been found that they are capable of supporting a respectable number of species of both animals and plants (Hansson et al., 2005; Vermonden et al., 2009; Le Viol et al., 2009).

Bastien, Arthur & McLoughlin (2011) carried out a survey, through the application of a structured questionnaire, about the potential value to residents of living in close proximity to a SUDS pond. Their findings indicated that people generally prefer to live close to ponds or regularly visit ponds in their vicinity, and are attracted most because of pond's wildlife. Their results also show that although the pond's characteristics are not the main factor influencing the choice to move into an area, but its effect is markedly positive.

There is an increasing pressure on planners and developers to design to provide green infrastructure and green spaces. SUDS can help in meeting this challenge and improve development by creating habitats that encourage biodiversity and simultaneously provide open green space (CIRIA, 2010; Andersson and Colding, 2014).

2.4.4. Water Resource Benefits

Some SUDS techniques that soak water into the ground can also recharge underground aquifers where there is no risk of polluting the aquifer (CIRIA, 2010). To be more specific, SUDS can capture, or harvest rainwater that can be used for functions that do not require treated water from the mains (for example, cisterns for flushing toilets, irrigations, etc). This may in effect contribute to water efficiency and, depending on the scale of the system, can contribute to localised flood risk management (CIRIA, 2010).

2.4.5. Community Benefits

Green infrastructure is, in the main, a public resource, available for use by the 80 per cent of the population who live in towns and cities (Forest Research, 2010). Green space, ponds, etc, have potentials for enhancing social cohesion; they can bring people together, and can improve community cohesion especially as different social groups engage with each other.

Wetlands can also serve as wildlife parks with stepping stones, boardwalks and islands. Similarly, ponds with foot paths, benches, picnic tables, etc, can also be exciting social and recreational areas. Ponds and wetlands will be assets to the community, enhancing the quality of life, by providing attractive and calm green space within the built environment CIRIA, 2010).

2.4.6. Recreational Benefits

Good quality, accessible green space and infrastructure can provide many potential health and wellbeing benefits (Velarde et al., 2007). The most significant of these can be grouped into three broad categories (Forest Research, 2010): (1) increased life expectancy and reduced health inequality; (2) improved levels of physical activity and health; and (3) promotion of psychological health and mental well-being. Access to green space has been found to raise levels of physical activity, which in turn improves individuals' health. Green space can also have a beneficial impact on mental well-being and cognitive function (Velarde et al., 2007). The evidence strongly suggests that, at their best, green spaces can help reduce health inequalities and that both the improvement of existing, and creation of new, green infrastructure should be prioritised, especially in areas of greatest need.

2.4.7. Educational Benefits

Barbosa et al (2012) concluded that SUDS should be seen as an opportunity for development and improvement of social, educational and environmental conditions in urbanized and surrounding areas. Many SUDS components have been used for recreational and educational purposes with schemes located in school playgrounds

(CIRIA, 2010). Some schools include SUDS to manage surface water that also provides an invaluable in-situ learning resource about water.

2.4.8. Development Benefits

Ling et al. (2007) have explored how a multifunctional approach to spatial planning of SUDS (drawing upon historical, ecological, communitarian, economic, and aesthetic functions) could underpin more sustainable regeneration in post-industrial landscapes. Delivery of SUDS can enable the granting of planning permission to developers. SUDS can provide savings on the overall construction and maintenance of drainage schemes (CIRIA, 2010).

Bastien, Arthur & McLoughlin (2011) carried out a contingent valuation of the benefits of ponds and found out that the additional value brought by SUDS amenity, when monetised, can offset a pond's initial construction costs and ongoing maintenance, hence ensuring the return on investment for developers.

2.5. SUDS Techniques

This section provides a brief and generic overview of the key SUDS techniques assessed and tested in this study. For further information on these techniques and related ones, the reader may wish to refer to Butler and Davies (2004), CIRIA (2004, 2007, 2010) and Scholz (2006, 2010).

2.5.1. Permeable Pavements

Permeable pavements allow surface runoff to infiltrate through their surface and underlying construction layers, as opposed to flowing over it. They are mainly used for car parks and roads where traffic intensity is relatively low. The infiltrated rainwater is usually treated and subsequently stored before it infiltrates into the ground, reused or released to a drainage system or surface watercourse (CIRIA 2004; Scholz and Grabowiecki 2007).

The main surfaces that could be considered as part of permeable pavement construction include: modular permeable paving, porous asphalt, grass reinforcement, resin bound gravel, porous concrete, macro porous, sports surfaces, block porous paving. The potential use of these permeable pavements includes: pedestrian areas, private driveways, car parks, lightly to moderate trafficked roads, ports, playgrounds, schools, sports or track event surfaces (CIRIA, 2015).

Economic analysis shows that permeable pavement costs less on a lifecycle basis than traditional surfaces, with reduced maintenance costs outweighing increased capital costs (Environmental Agency, 2007). While extra excavations are required to lay it, replacing worn out paving blocks is usually less costly than the digging required in renewing worn out tarmac. It is estimated that nationwide application of permeable paving in place of 50% of current non-road hard surfaces (retrofitted at their 'end of life'), would provide savings of nearly £1.7bn (Environmental Agency, 2007). These benefits would stem from site owners and operators not having to pay drainage charges, and in cheaper maintenance costs.

Three major types are described by CIRIA (2007) (Figures 2.4a – 2.4c). Type A (Fig. 2.4a) is a system where all the rainfall passes through the sub-structure into the soils beneath, and which implies that there will normally, be no discharge from the system. Type B system (Fig. 2.4b) consists of a series of perforated pipes at formation levels which will convey the proportion of the rainfall that exceeds the infiltration capacity of the sub-soils, to the receiving drainage system, thereby preventing the build-up of water collecting above the sub-grade, which consequently reduces the risks of soil stability. In Type C system (Fig. 2.4c), there is no infiltration, and the system is generally wrapped in an impermeable, flexible membrane placed above the sub-grade. Once the water has filtered through the sub-base, it is conveyed to the outfall via perforated pipes or fin drains. This type becomes useful especially where the water is to be harvested and reused, or where the water table is within 1 m of the sub-base.

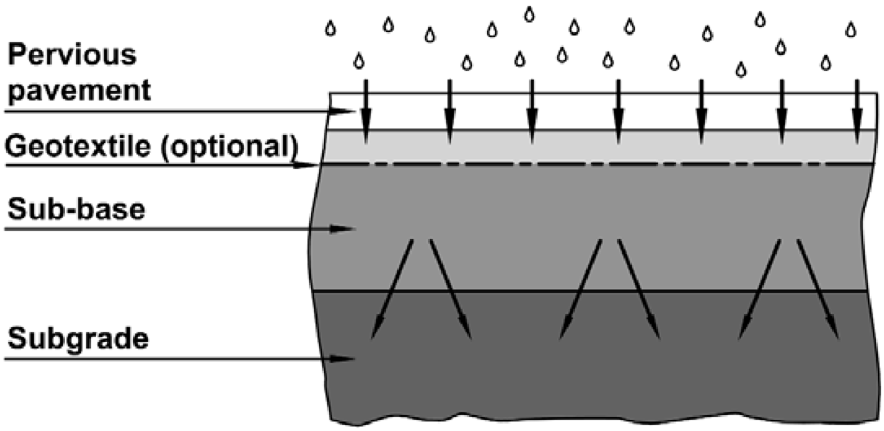


Fig. 2.4a: Permeable pavement system Type A – Total infiltration (CIRIA 2007).

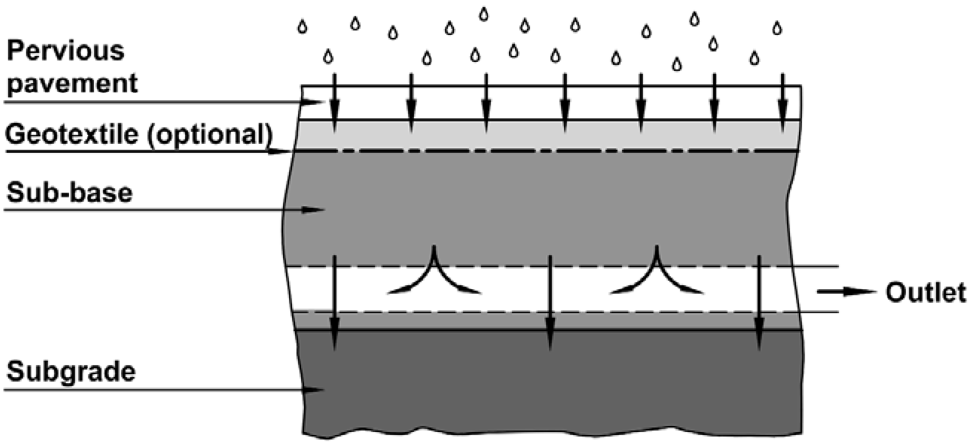


Fig. 2.4b: Permeable pavement system Type B – partial infiltration (CIRIA 2007).

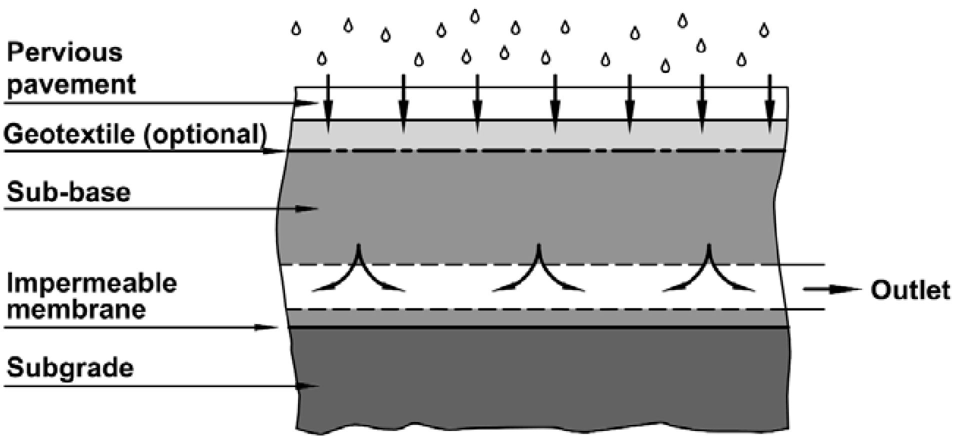


Fig. 2.4c: Permeable pavement system Type C – no infiltration (CIRIA 2007).

2.5.2. Filter Strips

Filter strips are a form of passive treatment, which are designed to treat runoff from adjacent impermeable areas (CIRIA 2004). A typical filter strip is a wide area of grass, or other dense vegetation, that is characterized by its gentle slope. The runoff is designed to flow as a sheet across the filter strip at a sufficiently low velocity so as to allow sediments to be filtered out, together with associated pollutants (CIRIA 2007). They are usually used as a pre-treatment technique before other SUDS techniques (e.g. swales, infiltration and filter trenches) in order to extend the life of downstream components. Filter strips are usually located between surface water bodies, small car parks and at the side of roads. High groundwater levels and steep gradients can generally be overcome by filter strips (Ellis et al. 2004).

To achieve optimum pollutant removal levels, flows for the water quality design storm should be lower than the height of the vegetation and should be limited to approximately 50 mm depth to maintain filtration (CIRIA, 2007). It is usually suggested that a 1 year return period and 30 minute event is taken as representative of an appropriate water quality treatment event. Maximum flow velocities of 0.3 m/s are recommended to promote settlement, and 1.5 m/s to prevent erosion during extreme flows.

Manning's equation can be used to design the filter strip:

$$V = \frac{d^{1/2}S^{1/2}}{n}$$

Where,

V = mean cross-sectional flow velocity (m/s)

d = depth of flow (m)

S = longitudinal slope of filter strips (ie in the direction of flow) (m/m)

n = Manning's n roughness coefficient.

Table 2.1: Advantages and disadvantages of Filter strips (Adapted from CIRIA, 2007).

Advantages	Disadvantages
1. Well-suited to implementation of adjacent to large impervious areas.	1. Large land requirement.
2. Encourages evaporation and can promote infiltration.	2. Not suitable for steep sites.
3. Easy to construct and low construction cost	3. Not suitable for draining hotspot runoff or for locations where risk of groundwater contamination, unless infiltration is prevented.
4. Effective pre-treatment option.	4. No significant attenuation or reduction of extreme event flows.
5. Easily integrated into landscaping and can be designed to provide aesthetic benefits.	

2.5.3. Swales

Swales are a form of permeable conveyance system. A typical swale is a broad and shallow channel, which is lined with suitable vegetation such as grass. As in the case of filter strips, the vegetation that covers the swale slows down the rate of surface runoff, thus reducing peak flows, as well as filtering the particulate pollutants contained within it (CIRIA 2004). Charlesworth, et al. (2012) carried out a laboratory study on the potentials of using coarse grades of compost to replace some of the topsoil being currently used as underlying materials in constructing vegetated SUDS devices such as swales. They discovered the coarse grades of compost provided more pollutant remediation, and could therefore be used in other SUDS techniques such as permeable paving.

2.5.4. Green Roofs

Green roofs are covered with vegetation and are ideal for a range of flat or gently sloping roofs, and are well-suited for urban areas where space is limited. These roofs are capable of removing pollutants from rainwater by filtering, adsorption onto the substrate and retention by plants (CIRIA 2004).

2.5.5. Ponds

Ponds act as a form of passive treatment. They are usually cost effective (due to a high volume to area ratio) SUDS techniques making them popular to control storm water runoff. Ponds are able to provide enhanced wildlife and amenity benefits and should be designed to do so without compromising the primary function of it being part of a storm water management system. The degree of treatment achieved depends greatly on the residence time of the temporary storage, which typically ranges between twenty-four and forty-eight hours (CIRIA 2004; Scholz 2004).

2.5.6. Constructed Wetland

A constructed wetland contains water of varying depth across its area and consists of marsh or wetland vegetation. This is one of the most effective SUDS techniques at providing diverse wildlife habitat and pollutant removal. However, there are also long-held concerns over the dangers of using wetlands designed for pollution accumulation as wildlife habitat (Helfield and Diamond 1997). Wetlands are able to eliminate pollutants by both plants and aggregates filtering and screening particles. In order to improve the efficiency of a constructed wetland, inlet and outlet sumps are recommended to deal with excessive sediment, which can quickly overpower the shallow ends of the wetland (Scholz and Lee 2005).

2.5.7. Infiltration Trenches

Infiltration trenches are shallow excavations lined with a geotextile material and backfilled with stones, creating a small belowground storage reservoir. Storm water runoff that flows into the trench slowly infiltrates into the subsoil. Infiltration trenches are capable of removing pollutants by adsorption, filtration and microbial decomposition in the soil underlying the trench (Scholz 2006).

2.5.8. Soakaways

Soakaways are a form of source control, operating by dispersing surface runoff into the ground. Recent types of soakaways consist of open chambers (in contrast to holes in the ground filled with aggregates) to store large quantities of water (Scholz 2006; CIRIA 2007).

2.5.9. Infiltration Basins

Infiltration basins are open and uncovered areas of ground, and they are relatively shallow features, which can be constructed either by excavating depressions or embankments. If landscaped, they can be aesthetically pleasing and also add amenity value. Infiltration basins store storm water runoff, which gradually percolates through the soil of the basin. The soil's permeability and the water table depth are mainly responsible for the efficiency of an infiltration basin (Scholz 2006).

2.5.10. Belowground Storage Tanks

Belowground (or underground) storage tanks are sub-surface structures that entrap and store surface runoff. The stored water is released at a slow rate to reduce peak flows during medium or heavy rainfalls. If soil conditions are suitable and the water table is located at a significant depth below the chamber, the storage tanks can be designed to allow stored water to infiltrate into the ground thus encouraging groundwater recharge (Nanbakhsh et al. 2007). The stored water can also be reclaimed and used for irrigation, washing cars and flushing toilets (Scholz 2006).

2.5.11. Water Playgrounds

Water playgrounds have little effect on managing the quantity and quality of surface runoff. Their main purpose is, however, to enhance amenity value through recreational benefits by providing a variety of water features that individuals (particularly children) can interact with (Scholz 2006; Scholz et al. 2006).

The suitability of each SUDS Techniques to meeting the three goals of sustainability are summarized in Table 2.2.

Table 2.2: Summary of SUDS techniques and their suitability to meet the three goals of Sustainability (After Scott Wilson, 2008)

Management Train	Component	Description	Water Quality	Water Quantity	Amenity & Biodiversity
Site, Area	Green roof	Layer of vegetation or gravel on roof areas providing absorption and storage	●	●	●
Site, Area	Rainwater harvesting	Capturing and reusing rainwater for domestic or irrigation uses	○	○	○
Site, Area	Permeable pavements	Infiltration through the surface into underlying layer	●	●	○
Area	Filter drains	Drain filled with permeable material with a perforated pipe through the base	●	●	
Area	Infiltration trenches	Similar to filter drains but allows infiltration through sides and base	●	●	
Area	Soakaways	Underground structure used for store and infiltration	●	●	
Area	Bio-retention	Vegetated areas used for treating runoff prior to discharge into receiving water or infiltration	●	●	●
Area, Catchment	Swales	Grassed depressions, provides temporary storage, conveyance, treatment and possibly infiltration	●	●	○
Catchment	Sand filters	Provides treatment by filtering runoff through a filter media consisting of sand	●	●	
Catchment, Regional	Basins	Dry depressions outside of storm periods, provides temporary attenuations, treatments and possibly infiltrations	●	●	○
Catchment, Regional	Ponds	Designed to accommodate water at all times, provides attenuation, treatment and enhance site amenity value	●	●	●
Catchment, Regional	Wetland	Similar to ponds, but are designed to provide continuous flow through vegetation	●	●	●

Key: ● - Highly suitable; ○ - Suitable depending on design

2.6. Identifying Retrofit Opportunities

CIRIA (2012) described two main forms of retrofit opportunity. The first form relates to urban regeneration or site reconstruction where the primary aim is not necessarily that of drainage improvement, but of site development, replacement or regeneration of building enhanced urban environments and small local incremental improvements. It is generally referred to as Opportunistic retrofitting or "nibbling". It can include areas of improvement as part of green network strategies. The second form of opportunity is drainage driven, either to control flooding or pollution or both. This opportunity usually occurs across comparatively larger areas and can be considered to be more strategic than opportunistic retrofitting. This is referred to as Strategic retrofitting.

2.7. Previous Decision-support Tools for Retrofitting SUDS

A decision support tool is usually a screening process used to determine the most appropriate technique or combination of techniques for a site. A number of practitioners and researchers have reported the use of decision making frameworks for SUDS (both retrofitting and new construction). However, the development of retrofit SUDS remains a complex and difficult problem, and existing guidance is far from complete and not applicable to all situations (SNIFFER, 2006).

2.7.1. Swan and Stovin (2002)

Swan and Stovin (2002) at Sheffield University developed a SUDS retrofit decision-making framework, which uses a hierarchical approach in selecting a site for retrofitting. They developed flowcharts that could direct engineers in considering range of options in a logical manner which involved using different charts for each of institutional roofs, car parks, residential roofs and highways. The research focused on the description of the order of preference for introducing SUDS into different land use areas (Fig. 2.5).

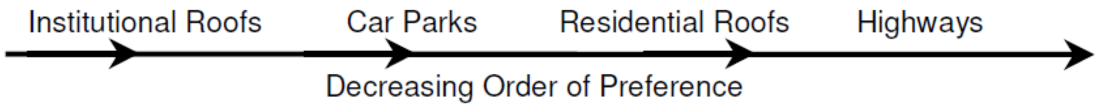


Fig. 2.5: Flowchart for the retrofits of SUDS site (Stovin and Swan, 2003).

The framework recommends the use of retrofit SUDS techniques as a tool to deal with drainage with first preference from institutional roofs, then to car parks, residential roofs, and finally highways. The rationale, which supports this hierarchy, is as follows (Hyder Consulting, 2004):

- They considered roof runoff to be cleaner than that from car parks and highways.
- They also considered drainage alterations at institutional buildings such as schools, colleges, hospitals, prisons etc (and particularly those in public ownership) as more likely to be simple to implement than those at numerous residential properties.
- They considered car parks to be relatively large paved areas that can generate significant amount of runoff. They considered some existing car parks to be oversized, and may have enough space for SUDS retrofitting. Therefore converting a hard paved surface to, for example, permeable paving, is likely to be less disruptive in a car park than in a highway.
- Residential roofs were also considered to have greater SUDS retrofit difficulties than car parks. A long row of terraced houses could, however, have a single drain that could be intercepted. Areas of council housing should be easier to alter than private homes. Even in private houses, a simple measure like the use of water butts provides a degree of attenuation.

However this study is biased towards Combined Sewer Overflow (CSO) spill reduction and sewer flooding problems, and so could not fully consider a wide range of other drivers that might lead to retrofit SUDS being considered, such as diffuse pollution, or the desire to ease restrictions on new development or inner city redevelopment arising from a lack of capacity within the existing sewer system (STIFFER, 2006).

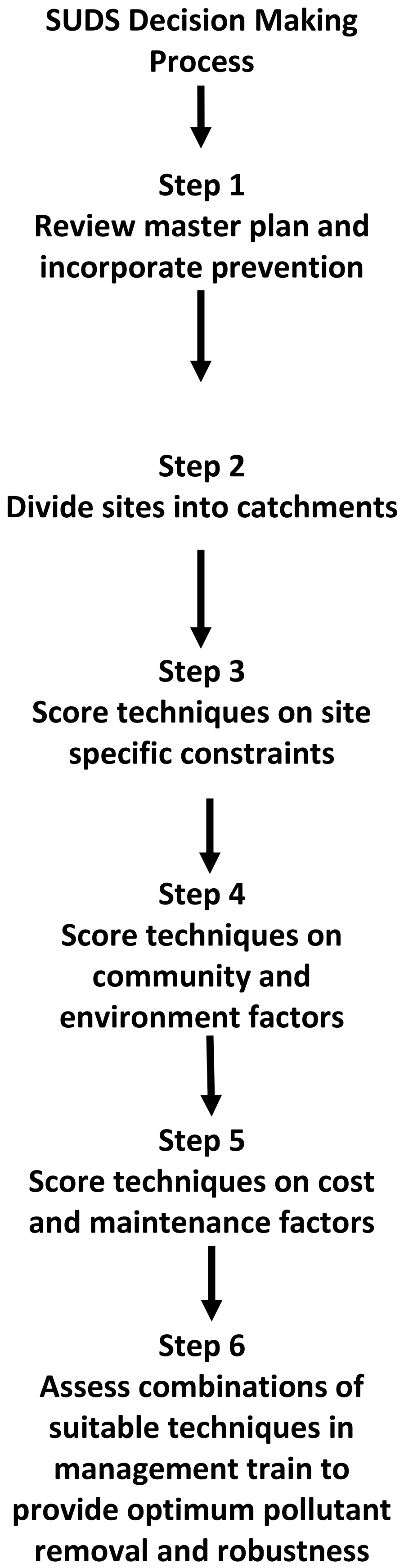
2.7.2. CIRIA (2004)

CIRIA Manual C609 (CIRIA, 2004; CIRIA, 2007) presented a Decision Criteria for Selecting SUDS techniques (Fig. 2.6) using a series of selection matrices. Each technique is given a score from 1 to 5 to indicate its performance against a variety of criteria such as: Hydrological and Land use, physical site features, economics and maintenance, community and environment. Techniques which score very high are selected for consideration and design. However, CIRIA selection model did not consider confidence levels of the assessor, elaborate ecosystem service variables, and retrofitting in the presence of mature trees.

2.7.3. Atkins (2004)

Although no schemes were constructed in connection with this project, some significant outcomes of generic value could be drawn from the desk study. The project however repeated the Swan and Stovin (2002) conclusions regarding the preference for large institutional/commercial properties for retrofitting SUDS, but costs for retrofits were found to be similar to conventional solutions. The need to apply appropriate modelling tools during the scheme design and evaluation process was also stressed. The lack of relevant catchment water quality modelling tools was highlighted, although the report did not address the issue of how to proceed in the absence of adequate models or data.

It should be recognised that Atkins (2004) report made significant advances over the Swan and Stovin (2002) methodology through its focus on practical implementation from an engineering/planning perspective (SNIFFER, 2006). In particular it developed a series of flowcharts detailing the steps involved in site selection and visibility assessment.



Step 1 – Review site master plan and identify areas where SUDS can be incorporated and any changes to the plan needed to enhance SUDS on the site. Identify where prevention techniques can be applied.

Step 2 – Divide the site into sub-catchments (based on location, land use, site layout or topography) to promote source control and keep areas where heavily polluted runoff could occur separate from other catchments (for example, lorry parking separate from roof drainage).

Step 3 – Score each technique on the basis of its pollution reduction performance, hydrological control effectiveness, land use and physical site features (Tables for these scorings are provided). The scores for each parameter should be inserted in the columns on the SUDS decision sheet. Take into account the weightings (for various criteria – 1 if desired, 2 if essential). The overall scores may be compared to identify those techniques more suited to the site. This will screen out some techniques as unsuitable and reduce the number of techniques that need to be considered in Step 4.

Step 4 – From the techniques remaining after Step 3, identify the techniques that achieve the best balance between community acceptance and benefits, environmental benefits, cost and maintenance burden, and compliance with any regulatory requirements.

Step 5 – From the techniques remaining after Step 4, identify those techniques that can be used within the constraints posed by the economic and maintenance criteria. Again, this will reduce the list of techniques that are suitable.

Step 6 – Check the pollutant removal efficiency and design robustness of combinations of techniques to determine the optimum combination of techniques that are to be placed in series to give the required design confidence and provide a management train.

Fig. 2.6: An algorithmic presentation of SUDS decision-making process by CIRIA, (Adapted from CIRIA, 2004)

It also stressed the need to engage relevant stakeholders at an early stage, and demonstrated the sufficient time required to select appropriate sites and obtain land owner's approvals.

2.7.4. SWARD Project

The SWARD project (Sustainable Water Industry Asset Resource Decisions) produced a framework that may be used by water service providers to enhance the way sustainability is incorporated into decision making process relating to water service provision (Ashley et al., 2004).

The SWARD guidebook indicates a case study of the application of Decision Support Process (DSP) that will enable the reduction of escape of sanitary waste from the sewer system. As with conventional solutions, such as installing screens, a range of options were proposed. They included a 'Think Before You Flush' (TBYF) campaign, and the retrofit of storm water source control to reduce overflow spills. The case study presented the need for the decision makers to consider alternative approaches which might have initially appeared to be purely engineering problems.

2.7.5. Ellis et al (2004)

Ellis et al (2004) proposed a multi-criteria decision support framework for the selection of SUDS techniques. Although this work was intended for SUDS in connection with new developments, it did not provide an example of the use of multi-criteria analysis in the selection of SUDS techniques but proposed a set of appropriate decision-making criteria.

Eventually when the framework was made available for practical use, stakeholders opted for sites ranked third out of four in the analysis, due to various local interests and practical constraints (STIFFER, 2006). This shows the danger of trying to develop a generic approach to decision making process, as each potential SUDS project would be expected to have its own specific stakeholder priorities and some practical constraints.

2.7.6. Scholz (2005)

Scholz (2005; 2006) as part of the Glasgow Strategic Drainage Plan (GSDP) put forward a SUDS techniques decision support tool with the aim of helping planners in identifying appropriate SUDS techniques for specific locations. The tool put into consideration the social factors such as the public acceptability of SUDS, economic factors such as the value of land, hydrological factors such as proximity to water courses, catchment area and run-off, water table level, and environmental factors such as potential for ecological impact.

The tool tended towards favouring swales, ponds and wetlands as retrofit SUDS techniques. However, it is not clear how the tool should be deployed to address specific drivers (e.g. flooding and/or water quality) at the catchment scale or how the tool helps to identify of prioritise disconnection opportunities (STIFFER, 2006). Moreso, the approach did not acknowledge the role of hydraulic modelling during an option's appraisal process.

2.7.7. Singh et al (2005)

Singh et al (2005) tried making use of the Swan/Stovin approach for a drainage area in Glasgow. Their work presented opportunities to improve upon the framework from a number of perspectives. They showed the importance of identifying separately-sewered areas that drills into combined sewers as they may be easier to disconnect from the system into regional SUDS devices.

They also showed that, in situations where water quality is the priority driver, it may be more preferred to disconnect surfaces that are associated with higher levels of contamination (e.g. parking areas on industrial sites) rather than cleaner surfaces, such as roofs. However, such approaches would need to ensure that any SUDS technique chosen could effectively treat any anticipated pollutant loadings, so that there would be no increase in the risk of groundwater contamination.

Singh et al (2005) also highlighted the need to integrate drainage planning with land use planning. They proposed that the retrofit methodology should also include a hierarchy for open spaces especially for larger SUDS in which vacant or abandoned areas could be preferred over parklands, with playing fields and private lands being least favourable.

2.7.8. Viavattene et al, (2008)

The key drivers behind the development of this decision support tool are firstly, the development of a Geographic Information System (GIS) tool which enables stakeholders to identify potential sites for the location of Best Management Practices (BMP), and secondly the integration of multi-criteria analysis approach to support wider considerations involved in urban decision processes (Viavattene et al, 2008).

However difficulties associated in the collection of field data were identified as a barrier limiting the implementation of decision-support systems in general and the integration of data within a GIS format in particular. They tried to apply this tool to the Eastside Urban Development (a 170 ha area close to the centre of Birmingham) but only a limited amount of data were accessed. This idea is still in its development stage.

2.7.9. Moor et al, (2012)

Moor et. al., (2012) introduced a geographic information system (GIS)-based decision support tool that could be used to select not only areas where sustainable drainage systems (SUDS) could be retrofitted within a large catchment (>100 ha), but also to allow for discrimination between suitable SUDS techniques based on their likely feasibility and effectiveness. The tool was applied to a case study catchment within London, UK, with the aim of increasing the quality of the receiving water by reducing combined sewer overflow (CSO) spill frequency and volume. The key benefit of the tool as presented was to allow rapid assessment of the retrofit SUDS potential of large catchments. It is not intended to replace detailed site investigations, but may help to direct attention to sites that have the greatest potential for SUDS retrofitting. This tool, however, could be seen as being biased towards CSO and stormwater disconnections using a disconnection hierarchy, and does not consider ecosystem service variables.

2.7.10. Stovin et al (2013)

Stovin et al., (2013) looked at the potential to retrofit SUDS to address Combined Sewer Overflow (CSO) discharges into the Thames Tideway catchment. They developed a two-stage process for evaluating a specific stormwater management need at the catchment scale: (a) Global disconnection scenarios which enabled a rapid assessment to be made of what might be achieved with various levels of disconnections, based on mapping of land uses and catchment hydraulic modelling. (b) an automated GIS options which could enable retrofit SUDS options to be identified.

However, their GIS based tool tended to focus on single source control measures, whereas in many contexts, site or regional scale controls may be more feasible and SUDS treatment trains would be more preferable from a water quality perspective.

2.7.11. CIRIA (2015)

In November 2015, CIRIA (2015) published a new SUDS manual (C753) which stressed the need for, and supported the early involvement of the different stakeholders and all other professions that have parts to play in SUDS implementation. It covers the planning, design, construction and maintenance of SUDS which will enable their effective implementation within both new and existing developments. The manual mainly focused on designing to achieve the main SUDS criteria of water quality, water quantity, amenity and biodiversity and less on Decision Criteria for Selecting SUDS techniques. The manual did not consider the ecosystem service variables. However, it included guidance on the design of SUDS schemes that use trees, such as designing an infiltration tree pit for a civic street but did not provide guidance on the wider issues of using trees in urban planning and design.

2.8. Expert Judgement

An expert judgement could be seen as the use of structured or unstructured inputs from different individuals who have specialist knowledge of the field in question. O'Hagan et al (2006) defined an expert as "someone who has great knowledge of the subject matter. However, expertise also involves how the person organises and uses that knowledge". Ferrell (1994) defined it as "a person with substantive knowledge about the events whose uncertainty is to be addressed".

Curt, Talon and Mauris (2008) stated that in some engineering cases, some characteristics or properties of a system are very difficult to quantify especially by instrumentation due to their cost or lack of reliable instrumental sensors. Therefore human evaluation is thus widely accepted as a tool for the evaluation in various domains. Visual inspection is a key item in civil engineering measurements, for example, for the surveillance of dams: cracking, differential movements, seepage, vegetation presence or sinkhole are examples of visual measurements assessed by experts during dam reviews (Curt, Talon & Mauris, 2008).

The estimation of uncertainties associated with expert judgment needs to be undertaken consistently to be informative. Human judgment may vary considerably, and involves an appreciation of reality and what is a realistic solution to a given problem and an understanding of the importance of making the right choice about what action to take

(Stewart and Roebber, 1997). Confidence estimations are affected by ones familiarity with a topic, experience with probabilistic assessments, the level of difficulty of a task, and the environmental context in which the task is performed (O'Connor, 1989).

Research has proven that a group's level of judgment usually outperforms that of an average individual due to the sharing of responsibility between the group members. This sharing, in turn, leads to an increase in their confidence to communicate judgments (Schultze et al., 2012).

Knowledge used by engineers to make judgments is not entirely of scientific nature, although a substantial part is derived by science, but is based on experimental evidence and on empirical observations of materials and systems. Understanding is built-up over time as a result of continuous unquantifiable but improving judgments and choices (Ferguson, 1992; Holt, 1997). The introduction of a weighting system can address differences between assessor groups with different scientific backgrounds.

Previous studies indicate that good expert judgment performance can be observed when both the scientific validity of an estimated observation and the learnability of the estimation by the assessor are high. Poor expert opinion may occur if at least one of these factors is low (Bolger and Wright, 1994).

2.9. Multiple Criteria Decision Analysis

Multi-Criteria Decision Analysis (MCDA) is a decision making technique or tool which is widely considered to be very useful in resolving conflicts related to the decision making process (Javanbarg et al, 2012). MCDA consists of a set of principles and tools to assist a decision maker in solving a decision problem with a finite set of alternatives compared according to two or more criteria, which are usually conflicting (Chen, 2006). The theory of MCDA assumes that criteria are always well-defined, however, the examples of the work carried out by Fenton and Neil (2000) confirmed that this is not always true for real-life problems. MCDA usually involves: (i) the set of possible (mutually exclusive) *actions* we can take (the alternatives); (ii) a set of *criteria*, which are functions defined on actions; and (iii) a set of *constraints* which are properties of the criteria; (these can also be thought of as the *preferences*) (Vincke, 1992).

One of the most commonly used MCDA is the Saaty's Analytical Hierarchical Process (SAHP) tool which uses hierarchical structures to represent a problem and then develop priorities for the alternatives based on the judgment of the user (Saaty, 1980). The SAHP process involves defining the unstructured problem, developing AHP hierarchy, pair-wise comparison, computation of relative weights, consistency check and finally obtaining overall rating for obtaining desired results (Lee et al, 2008; Jaiswal, et. al, 2015). The Saaty's AHP (SAHP) in combination with GIS have been used in watershed management plan (Oyatoye et al. 2010), forest management (Kafaky et al. 2009), and in identification of erosion prone areas (Jaiswal et al 2014). MCDA can also be applied to a range of regional issues such as industrial development (Nijkamp and van Delft, 1977), waste management (Shmelev and Powell, 2006), renewable energy (Madlener and Stagl, 2005; Gamboa and Munda, 2007) and environmental policy (Omann, 2000), sustainability problems in general (Munda, 2005a; Shmelev and Rodriguez-Labajos, 2009), biodiversity in conservation planning (Moffett, 2006).

2.10. Ecosystem services and urbanisation

The benefits human beings may obtain from the semi-natural environment (e.g., urban green space) can be referred to as ecosystem services (Millennium Ecosystem Assessment, 2005). Defra (2011) defines ecosystem services as the benefits individuals gain from the goods and services (Table 2.3) produced by nature and its natural systems (Defra, 2011). The natural resources such as timber and water, and functioning natural systems such as healthy fertile soils, clean water (Walsh et al, (2012) and air, and a regulated climate are essential for human wellbeing, security and economic prosperity (Millennium Ecosystem Assessment, 2005). A high biodiversity helps to sustain the natural environment and is thus an important factor for ecosystem service provision. For example, a diverse range and a substantial number of urban trees support wildlife and human well-being.

Table 2.3. Examples of ecosystem services associated with urban water components together with ecosystem goods, benefits and possible units of measure, (Adapted from: Lundy and Wade, 2012).

Categories of ecosystem services	Types of ecosystem services	Ecosystem goods and benefits	Examples of units of measurements
Supporting services	Primary production	The goods and benefits of sustaining services are their role in facilitating other services to take place	g C m^{-2}
	Production of oxygen		g $O_2.m^{-2}$
	Soil formation		cm $year^{-1}$
	Water cycling		% permeability
	Provisioning of habitat		hectares
Provisioning services	Food	Meat and vegetables	tonnes/hectare
	Water	Portable and non-portable water	litres/hectare
	Renewable energy	Hydropower	Mega watts
	Genetic resources	Pollutant degrading species	cfu/ml
Regulating services	Climate regulation	Reduced urban temperatures	^oC
	Water regulation	Reduces runoff volumes/velocity	m^3; ms^{-1}
	Erosion control	Stabilisation of sediments	g/m^2
	Water purification	Removal of pollutants	mg/l
Cultural services	Spiritual value	Mental well being	Number of users (reduced demand on mental services)
	Educational value	Increased environmental awareness	kg (reduced littering of water bodies)
	Aesthetics	Increased house prices	% (increase in house price
	Recreation	Physical well being	% (reduced levels of mortality)

Costanza et al. (1997) introduced the concept of ecosystem services, the associated values and corresponding categories. The ecosystem approach is a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way. The increasing human population size, economic growth and global consumption patterns place pressure on environmental systems. It follows that the provisioning of ecosystem goods and services is affected (Seppelt et al., 2011). The concept of ecosystem services stayed much the same until de Groot, Wilson and Boumans (2002) published a framework diagram and a table in an attempt to distinguish between ecosystem functions, processes, goods and services. Brown, Bergstrom and Loomis (2007) subsequently defined ecosystem services as the results of ecosystem processes that either directly sustain or enhance human life or maintain the quality of ecosystem goods.

A number of official documents such as the Natural Environment White Paper (Defra, 2011), the UK National Ecosystem Assessment (2011) and TEEB (2011) have identified four broad categories of ecosystem services generally referred to as supporting, regulating, provisioning and cultural. All existing ecosystem services are strongly linked to one another and to other types of ecosystem services. The impacts of supporting services on nature take place over a long period of time and are indirectly beneficial to human life. They refer to all ecosystem services that provide a basic infrastructure of life (UK National Ecosystem Assessment, 2011), and it is due to this that all other ecosystem services, which do not fall within this category, depend on their existence for their own continuation. Supporting services are strongly interrelated to one another by an extensive range of chemical, physical and biological interactions (UK National Ecosystem Assessment, 2011).

Tzoulas et al. (2007) provided a detailed literature review on ecosystem services in the urban environment. TEEB (2011) and other guidance documents such as Moore and Hunt (2012) have produced list of ecosystem services. TEEB (2011) proposed a comprehensive list of ecosystem service variables of generic nature, while Moore and Hunt (2012) chose a smaller set of variables particularly adapted for constructed wetlands and ponds.

Euliss et al. (2011) proposed a modeling framework to allow estimation of conservation practice and program effects on various ecosystem services at different temporal and spatial scales. This modeling approach could provide the broad view needed by decision-makers to avoid unintended negative environmental outcomes, and to communicate to society the positive effects of conservation actions on a broad suite of ecosystem services.

The ecosystem services classed within the category of regulating services are very diverse and include all those ecosystems that provide benefits through the regulation of ecosystem services. The goods that are obtained from ecosystem services are referred to as provisioning services (UK National Ecosystem Assessment, 2011). The goods obtained can be distinguished depending on the degree of human interference. Goods that have been yielded from nature with minimal interference from humans can be referred to as 'natural production', while goods that have had a higher level of human interference, such as the use of fertilizers and pesticides, can be referred to as 'joint production' (Slootweg et al., 2010).

Ecosystem services, which are present due to environmental settings that provide recreational areas where individuals can interact with nature and each other (UK National Ecosystem Assessment, 2011), find spiritual fulfillment and mental development are known as cultural services. These services are, however, rather subjective, dynamic and difficult to quantify. However, Sander and Haight (2012) estimated the economic value of cultural ecosystem services in an urbanizing area using hedonic pricing. They found out that many aspects of the aesthetic environment significantly impacted home sale prices.

The continuing increase in urban population is putting a considerable strain on provisioning services such as food, fibre, water and energy, preventing the efficient delivery of numerous regulating, supporting and cultural services. Urban areas are increasingly being faced with issues such as elevated surface runoff and more heat island, which result in alterations of the local energy exchange and hydrology, thus having a negative impact on regulating services for climate, soil and water quality, and noise. In the UK, roughly 30% of ecosystem services have been identified as declining, while many others are considered to be in a reduced or degraded condition (UK National Ecosystem Assessment, 2011).

A more resilient semi-natural environment needs to be created to protect ecosystems to counteract the negative impacts of urbanisation. This can be achieved by bettering habitat management to improve the quality and size of existing wildlife sites, creating physical corridors to improve connections between SUDS sites, creating new habitats by planting more urban trees and lessening the strain on wildlife by reviving the wider environment (Lawton et al., 2010). Some success in improving the ecological status over the past ten years has been accomplished through the Water Framework Directive (European Union, 2000) by improving the quality of many water bodies (UK National Ecosystem Assessment, 2011).

Ecosystem service assessment is dynamic considering that the built environment constantly changes (Eigenbrod et el., 2011) and the scientific knowledge of associated processes develop further. For example, surface permeability and green roof runoff estimates may be different in the future. It follows that SUDS recommendations will change over time

2.11. Challenges and Shortcomings in the Implementation of Ecosystem Services

Seifert-Dähnn et al (2015) briefly reviewed the challenges and shortcomings in implementation of the ecosystem service (ES) approach in water management and indicated possibilities to overcome them. Their recommendations included (1) the development of practical, usable guidance documents, (2) sharing of knowledge in ES assessment databases, (3) identification of means by which the "dominance" of monetary valuation can be overcome, (4) collection of evidence on if and how ES assessment results are used in decision making, and (5) a stronger involvement of stakeholders.

2.12. Urban trees

Urban trees are usually characterised by their common name, botanical name, height, spread (crown), and diameter at breast height (DBH), etc. Although, urban trees grow at different rates their performance is usually affected by environmental factors such as: soil, nutrients, sunlight, water compaction of the soil materials, etc. Some researchers have tried to stipulate a guide or formulae for estimating the age of some urban trees (Fichler, Clark & Worbs, 2003; Kalliovirta & Tokola, 2005; Sharma & Parton, 2007). One of the major problems in understanding the growth trends in trees is the difficulty of separately quantifying the effects of tree size and age (Das, 2012; Bowan et al., 2013; Stephenson et al., 2014). Matsushita et al (2015), using careful statistical control of age and size covariation, presented a novel two-dimentional log-normal tree growth model.

Some researchers have classified trees based on their size (height, spread and DBH), for example, Armour et al (2012) interpreted a large species tree as being one that would grow in excess of 15m high when mature, provided their growth is not restricted by constraints to root development.

TDAG (2014), in their attempt to guide for the integration of trees in urban development, encouraged the involvement and collaboration of different stakeholders such as: designers, local authority planners, project managers, tree officers/specialists, highway engineers, drainage engineers. This may be as a result of the many roles that trees play in urban settings.

CIRIA (2012) promotes the planting of large urban trees. Researchers claim that on average the annual net benefit of planting large tree species is 44% greater than for a medium tree species and 92% greater than for a small tree species (McPherson et al., 1999). They also state that it takes less than five years from planting for the net benefits of large species trees to outweigh net costs. Financial benefits of retaining and planting trees are increased property prices and land values, faster property sales, reduced energy costs for property owners and businesses through microclimate regulation, and improved tourist and recreational facilities. Furthermore, social and environmental benefits of trees include regulating the microclimate, attenuating and filtering water, attenuating noise, improving air quality and sequestering carbon, provide habitat resource (enriching biodiversity and promoting access to nature), improved physical and mental health, better childhood development and overall well-being, enhanced social cohesion, reduced flood damage, and improved workplace productivity and hospital recovery rates.

However, some trees at certain locations may have obvious associated negative effects. These include health and safety issues such as fall of fruits and pine cones on humans, damage to the built environment due to vigorous root growth, blockage of gutters, down-pipes, gullies and permeable pavements by fruits, pine cones and leaf litter, deterioration of driving conditions due to leave cover on roads in autumn or the occasional visual obstruction of bends due to their large size (Scholz and Uzomah, 2013). Moreover, this leads to maintenance activities such as road sweeping to remove the leaves or branch pruning.

2.13. Benefits of Urban Trees

Urban trees are linked to a wide range of benefits including economic, environmental and social as well as health and well-being (Scholz, 2010).

2.13.1. Environmental Benefits

Trees absorb considerable quantities of carbon dioxide, which is the predominant greenhouse gas. This is also called carbon sequestration or mitigation. The term mitigation refers to activities aimed at reducing greenhouse gas emissions and/or removal of carbon dioxide from the atmosphere (Malhi and Grace, 2000). Trees filter, absorb and reduce pollutants such as: Ozone, Sulphur dioxide, Carbon monoxide, nitrogen dioxide, dusts, particulates and noise (Jim and Chen, 2008). Trees also produce Oxygen during photosynthesis.

Trees reduce localised extremes in temperatures, cooling the urban environment in the summer and warming it in the winter (Leuzinger, et. al., 2010; Sitawati, et. al, 2011; Doick and Hutchings, 2013). Based on the research carried out by Leuzinger et.al., (2010), some trees are better at reducing street temperatures. The magnitude of cooling from a shade tree depends on: crown shape, crown density, tree growth rate and longevity, and placement of the tree relative to the building to be shaded (Doick and Hutchings, 2013).

Researchers stated that towns and cities with less trees are usually a degree or two warmer than surrounding rural areas, as a result of the urban heat island (UHI) effect (Gill et al, 2007; Forest Research, 2010). The UHI is caused by two main factors: the absorption of direct solar radiation by buildings and other man-made surfaces, and the lack of vegetation in urban areas (Heidt and Neif, 2008). Gill et al. (2007) suggested that increasing the current area of green infrastructure in Greater Manchester by 10% (in areas with little or no green cover) could result in a cooling of up to 2.5 °C under the high emissions scenarios based on the UK Climate Impacts Programme (UKCIP02) predictions.

Trees have long been used as windbreaks as they form a physical obstacle and inhibit wind speed and turbulence (CIRIA, 2012). This in turn can be used to provide wind shelter for buildings.

Trees and other plants help remediate soils at landfills and other contaminated sites by absorbing, transforming, and containing a number of contaminants (Thaler, 2011).

2.13.2. Stormwater and Flood Control Benefits

Trees act as point source flood control by reducing the water content of the soil through evapo-transpiration thereby aiding infiltration, intercepting rainfall by the leaves and barks. Rainfall interception is maximised with large, evergreen tree species (Xiao and McPherson, 2002). A single large tree can release up to 400 gallons (1820 litres) of water into the atmosphere each day.

Research has shown that urban forest can reduce annual stormwater runoff by 2–7 percent, and a mature tree can store 50 to 100 gallons of water during large storms (Fazio, 2010). Green streets, rain barrels, and tree planting are estimated to be 3-6 times more effective in managing stormwater per $1,000 invested than conventional methods (Foster, Lowe and Winkelman, 2011).

CIRIA (2015) highlighted some tree characteristics that increase their effectiveness in reducing surface water runoff and in filtering pollutants. Such characteristics include: widespread and dense canopies (McPherson et. al., 2002), long life expectancies, fast growing rates, high tolerance to summer drought, tolerance to saturated soils, extensive root system, rough bark, dull foliage surface (CRWA, 2009), etc. Day et. al. (2008) concluded that root penetration of compacted subsoil can increase infiltration rates by as much as a factor of 27.

2.13.3. Economic benefits

The presence of urban trees increases property prices (Sander et. al., 2010). Donovan and Butry (2010) carried out a study in Portland, Oregon and established how much street trees increase the value of a house. They quantified the impact of street trees on Portland‘s housing market and found, that on average, street trees add $8,870 to sales price and reduce the time on the market by 1.7 days. They also found out that the benefits of street trees spill over to neighbouring houses.

When planted strategically urban trees can reduce fossil fuel emissions by reducing fuel costs for heating and cooling buildings. Lowering air-conditioning demand leads to energy and cost savings and reduces the emission of waste heat energy (Emmanuel, 2005).

2.13.4. Social Benefits

Trees increase the aesthetic value of a place, and provide amenities including ecosystem services (Scholz and Uzomah, 2013). Trees can become living witnesses to histories and evidence of cultures (Catt, 1993). They may also symbolise community focal points. Trees provide habitats for a broad range of wildlife (Fuller, 2003). Trees mark the changing seasons with leaf changes and floral displays.

2.13.5. Health and Well Being

Trees reduce stress and illness by providing psychological refreshment and a sense of well-being through softening the built environment, creating character and a sense of place and permanence (Ulrich et.al., 1991; Botkin and Beveridge, 1997; NUFU, 1999).

Trees reduce direct exposure to UV rays. The sun's UV rays can have adverse health effects on the skin and eyes. High levels of long-term exposure to UV rays are linked to skin cancer. The shades provided by tree canopies can help lower UV exposure (Heisler and Grant, 2000; Heisler, et. al., 2002)

2.14. Permeable pavements, urban trees and linked ecosystem services

This section provides a brief and generic overview of permeable pavement systems within the SUDS context. For further information on this technique and related ones, the reader may wish to refer to Butler and Davies (2011), CIRIA (2004, 2007, 2010) and Scholz (2006, 2010, 2013).

Permeable pavements allow precipitation to infiltrate through their surface and underlying construction layers, as opposed to flowing over it. They are mainly used for car parks and roads where traffic intensity is relatively low. In some cases the infiltrated rainwater is treated and subsequently stored before it infiltrates into the ground, reused or released to a drainage system or surface watercourse (CIRIA, 2004; Scholz and Grabowiecki, 2007; Scholz, 2013).

Permeable pavement designs vary greatly. In addition to supporting traffic loads, the general principle of permeable pavement systems is simply to collect, treat and infiltrate freely any surface runoff to support groundwater recharge (CIRIA, 2007). In comparison to traditional drainage systems, storm water retention and infiltration is a sustainable and cost effective process, which is suitable for urban areas. Moreover, permeable pavement systems have many potential benefits such as reduction of runoff, recharging of groundwater, saving water by recycling and prevention of pollution (Scholz and Grabowiecki, 2007; Scholz, 2013).

Permeable pavement systems have not only been set-up as a sustainable drainage solution, but also as a technology for pollutant control especially regarding surface runoff from areas used as roads or parking spaces, where contaminated water may infiltrate into the underlying soil. Harmful pollutants such as hydrocarbons and heavy metals in surface runoff have the potential to endanger soil and groundwater resources when they are not sufficiently biodegraded and/or removed during infiltration (Scholz, 2013).

Reductions in suspended solids (originating, for example, from road grit and degraded leaves), biochemical oxygen demand, chemical oxygen demand and ammonia levels in comparison to highway gullies not only demonstrate the high treatment efficiency of various permeable pavement systems, but also that there is no need for frequent maintenance, unlike with gully pots (Scholz, 2010).

Moreover, hydrocarbon pollution and mineral oil deposition onto urban surfaces have been problems most effectively addressed by permeable pavements. Research has also shown that the structure itself can be used as an effective in-situ aerobic bioreactor (Scholz, 2006, 2013).

2.15. Side Walks (Permeable and Impermeable Pavements) of Road Structures

A Sidewalk is a paved strip, running along one or both sides of a road, and providing a passage route for pedestrians including wheelchair users. Sidewalks can either be of permeable or impermeable pavements. Trees planted near sidewalks improve the pedestrian experience, improve the aesthetic appearance of the street, serve as visual and auditory buffer between the pedestrians and the traffic, and provide shades to road users. Sidewalks can be damaged by trees, vehicle accidents, water main breaks, grade subsidence, age, etc. However, damage from trees is the most common source of damage to sidewalks, and consists of cracks, lifting up, depressions (pulling down), and separating permeable pavements.

Figure 2.7 shows the different layers of a typical sidewalk in UK. The sub-base is usually made of a compacted granular material (Randrup et. al., 2003). The compaction of these underlying materials restricts tree roots from accessing the water and mineral resources contained in the soil. In order to address the issue of compacted soils limiting tree root growth, some researchers have developed a variety of structural soils that can be used as alternatives to typical compacted soils and often contain large proportions of aggregates to bear the weight of the overlying pavement and vehicular traffic in urban areas (Smiley et al., 2006; Grabosky et al., 2009; Beecham 2012). Smiley et al. (2006) conducted a study on tree growth in a variety of structural soil types and also trialled a method of suspending a pavement on piers above a non-compacted soil. They found that trees planted in non-compacted soil beneath the suspended pavement were generally larger, faster growing, and healthier, and had more root growth than in the other treatments (Beecham, 2012). This finding implies that trees planted in parks or other non-compacted areas will eventually grow bigger with the roots extending deeper into the soil, and will consequently cause less damage as the roots will come into contact with no surface structure.

Randrup et al. (2003) explained that a concrete or asphalt pathway can act as a barrier that prevents soil moisture loss by evaporation. This evaporation barrier causes the soil moisture to condense on the underside of the pavement because of temperature differences between the soil and the pavement. Tree roots are therefore naturally attracted to the condensation at the soil/concrete interface and this leads to pavement surface damage through the radial forces generated during root growth. Randrup et al. (2003) therefore proposed that pavements constructed from porous materials that limit condensation and lower the temperature under concrete slabs may reduce the incidence of rooting at the interface and the subsequent damage this can cause (See Figure 2.8 below).

Gilman (2006) carried out a research work on deflecting tree roots near sidewalks and found out that tree roots deflected by the vertical barriers were forced deeper into the soil, but many returned to the surface by the time they reached the opposite side of the walk. They also discovered that gravel under the sidewalk appears to hold promise for reducing sidewalk damage, especially on well-drained sites.

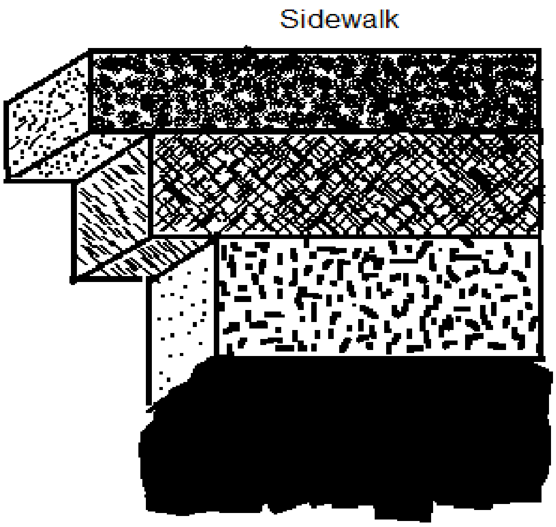


Fig. 2.7: A typical sidewalk cross-session in UK. (Adapted from Randrup et. al., 2003)

2.16. Urban Tree roots under impermeable pavements

When roots encounter dense soil, they change direction, stop growing, or adapt by remaining abnormally close to the surface (Bassuk, 2005). Fig. 2.8 exposes the behaviour of tree roots when constrained under impermeable pavements as discussed in section 2.14. This superficial rooting makes urban trees more vulnerable to drought and can cause pavement heaving. More so, if the dense soil is waterlogged, tree roots can also rot due to lack of oxygen. Healthy trees need a large volume of non-compacted soil with adequate drainage and aeration with reasonable fertility. The highly compacted soils required for constructing pavements do not allow root penetration.

Fig. 2.8: Surface rooting of trees growing in compacted soils (Source: Bassuk et. al., 2005 (permission to use this picture was granted by Prof. Nina Lauren Bassuk, on behalf of Urban Horticulture Institute, Cornell University)).

2.17. Structural Damage by Urban Trees

The root system normally provides the essential functions of anchorage (structural stability), absorption of water and nutrients and storage of vital food reserves. However, tree roots (and occasionally the shoots) can cause damage to structures such as permeable pavements and other sustainable urban drainage structures, impermeable pavements, kerbs, roads, footpaths, retention walls, houses, etc. Tree roots may cause damage to underground services by direct pressure on conduits as roots grow and expand in diameter, or by entry to hydraulic services such as sewer and stormwater lines which may then cause damage or blockage (Mather and Morton, 2008). Species that have large and vigorous root systems may also cause significant damage to public infrastructure, including roads, kerbs, footpaths, paved areas and underground services. These types of trees should be avoided. Forces exerted by radial growth of roots can lift light structures such as paths, curbs, paving slabs, boundary walls and occasionally single story buildings (e.g., garages or porches) (Biddle, 1998; Mather and Morton, 2008).

Several studies have found strong correlations between tree size and conflicts with infrastructure (Mather and Morton, 2008). Wagar and Barker (1983) found that large trees caused more conflicts than small trees. Also, more than half of the variation found for sidewalk conflicts was associated with tree diameter. Wong et al. (1988) found that most trees started to cause damage when they were 11–20 cm in diameter at breast height (DBH). However, most Oaks (*Quercus sp*.) and Horse Chestnuts (*Aesculus sp*.) did not cause damage until they were greater than 20 cm in DBH (Randrup et. al., 2003).

Barrel (2011) stated that tree roots can influence and cause damage to structures in ways such as: directly through root growth (Fig 2.9), directly through transmission of trunk movements through large roots, indirectly through shrinking of supporting soil. In further explanation of the direct damage through root growth, Barrel (2011) also stated that as tree roots grow in size, they will exert forces on anything they touch, which can cause damage if they come into direct physical contact with structures. However, there is a biological limit to how much pressure can be exerted through cell division and expansion, which means that only light structures such as hard surfacing, drains, small walls and small buildings can be damaged by this mechanism(Barrel, 2011). Roots do not have the capacity to lift heavier structures such as substantial garages or houses, and will distort or stop growing before they can exert sufficient pressure to cause damage. Damage to susceptible structures can occur on any type of soil and at any distance from the trunk that roots can reach. Damage caused by this mechanism will typically be progressive, with the degree of distortion gradually increasing over time (Figure 2.9).

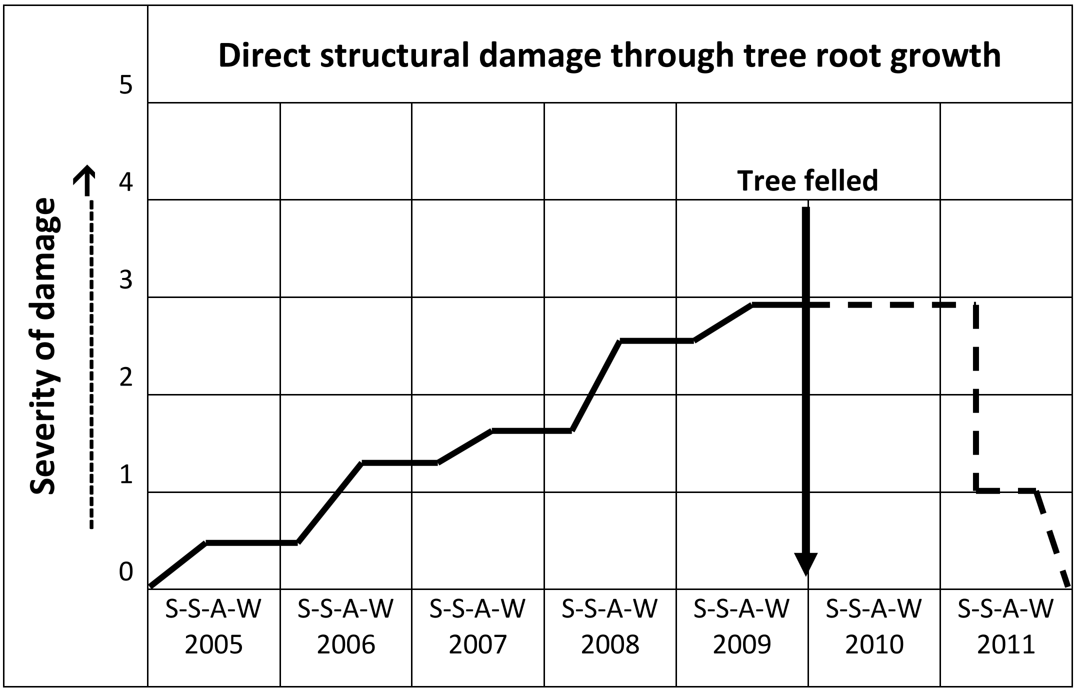


Fig. 2.9: Structural damage from tree root growth (Adapted from Barrel, 2011). (S-S-A-W = Spring, Summer, Autumn & Winter).

2.18. Root Protection Area

British Standard (BS 5837, 2012) defined Root Protection Area (RPA) as "Layout design tool indicating the minimum area around a tree deemed to contain sufficient roots and rooting volume to maintain the tree's viability, and where the protection of the roots and soil structure is treated as a priority". For single stem trees, the RPA can be estimated as an area equivalent to a circle with a radius 12 times the stem diameter (BS 5837, 2012).

However, RPA could be affected by: (a) past or existing site conditions (e.g. the presence of roads or structures); b) topography and drainage conditions; c) the soil type and structure; d) species, age, condition and past management.

2.19. Chapter Summary

This chapter discussed the need to rethink the philosophy of drainage systems by comparing the Combined Sewer system with the SUDS. Comparison was also made of the natural and urban catchments, and hence, the need for SUDS especially in the area of erosion and flood control. The benefits of SUDS were also discussed. It then briefly discussed the various types of SUDS techniques. The chapter also discussed and analysed previous attempts by some researchers to develop decision support tools for retrofitting SUDS in chronological order.

It then discussed urban trees and explored the benefits of urban trees. Conversely, the structural damage by urban trees was also reviewed. It also discussed the interaction between tree roots and permeable, impermeable and non-compacted surfaces. It then reviewed structural damage from tree root growth.

CHAPTER 3

METHODOLOGY

3.1. OVERVIEW OF METHODOLOGY

This work was carried out in three phases. This section therefore outlines the sequence of steps of the methodological approach undertaken. However, methodology described here, including its tables and figures, already formed part of publications extracted from this research work, For example, Phase 1 methodology descriptions are part of publication no. 1 and 2 on page xii, Stage 2 methodology descriptions are part of publication no. 3 on page xii, and stage 3 methodology descriptions are part of publication no. 4, on page xii.

PHASE 1 – The SUDS Decision Support Tool.

This involved the development and modification of the Decision Support Tool and its associated ecosystem services (Appendix A), and using them to assess the retrofitting choices of 100 sites in Greater Manchester (section 3.2). The methods applied in this section are used to make a decision on the most appropriate SUDS technique for each case study sites; options include permeable pavement, filter strip, swale, green roof, pond, constructed wetland, infiltration trench, soakaway, infiltration basin, belowground storage and water playground.

The developed decision support tool for the retrofitting of SUDS is given in Appendix A. The site assessment template was based on a combination of the frameworks developed by Scholz (2006) and Scholz et al. (2006) for retrofitting of SUDS techniques in Glasgow, Edinburgh and elsewhere, and the Construction Industry Research and Information Association (CIRIA) guidelines (CIRIA, 2004, 2007). However, both the initial framework and the CIRIA guidelines did not consider confidence levels, robust ecosystem services and a weighting system for different professionals to accommodate various stakeholders. 'Confidence Levels' were incorporated into the tool to reduce bias and uncertainty. In addition to the above, expanded and elaborate ecosystem service variables were introduced.

These were further explained in the following subsections:

- 3.2.1 gives an overview of Greater Manchester as an example case study.
- 3.2.2 explains the standard site assessment variables for 100 potential SUDS sites in Greater Manchester, and the decision making flow chart using the new ecosystem approach.
- 3.2.3 outlines a set of additional ecosystem service variables, and explains how they were used for the assessments.
- 3.2.4 explains the introduction of confidence levels in order to reduce uncertainties and increase reliability of the estimated values.
- 3.2.5 outlines the determination of sustainable drainage system techniques with traditional ‘community and environment’ variables.
- In contrast, section 3.2.6 outlines the determination of sustainable drainage system techniques with new ecosystem service variables.
- A comparison between the traditional and revised assessment methods is given in section 3.1.7.
- 3.2.8 assesses an approach of combining the traditional and new approach with each other.
- Finally, the tree determination method is outlined in section 3.2.9. This section gives the initial assessment of predominant tree species located in Greater Manchester.

PHASE 2 – The introduction of weighting systems for different professions.

The study and introduction of weighting systems based on the perspectives of the varying professional backgrounds of SUDS stakeholders, such as: drainage engineers, planners, ecologists, developers and social scientists. This is intended to make the tool more versatile, cheap and easy to be used by people of different professions (sections 3.3). Further reasons for this professional diversification were explained in Section 1.2. The variables used in the assessment of weighting factors were *aesthetics, land cost, habitat for species* and *safety*.

- 3.3.1 gives the evaluation of the variability of estimated variables and learning process of estimation.
- 3.3.2 gives comparison of variability with other cohorts within the University of Salford community.
- 3.3.3 discusses the extension of the questionnaire to the general public using the Bristol Online Survey platform.
- 3.3.4 discusses the application of the Decision Support Tool with the Different Professions perspective.
- 3.3.5. Data Analysis

PHASE 3 – Assessment of Tree Damage to Structures, and the evaluation of public acceptance of some tree species.

The study of the damage characteristics of some urban tree species to various urban structures, and also the study and evaluation of the aesthetics and public perceptions/acceptance of such tree species, so as to provide balanced modalities for best choice of trees for both retrofitting of SUDS and urban development projects (section 3.3). Structures studied include: permeable pavements, impermeable pavements, kerbs, roads, footpaths, buildings and retaining walls.

- 3.4.1 describes the selection of sites for tree damage analysis.

- Tree Damage Data Collection was discussed in section 3.4.2.
- Section 3.4.3 discusses tree damage analysis.
- 3.5.1. discusses the Arboretum's tree data collection for public acceptance evaluation.
- 3.5.2 discusses the Arboretum's tree assessment.

3.2. THE SUDS DECISION SUPPORT TOOL

3.2.1. Greater Manchester: an example case study

Greater Manchester, a sub-region in the Northwest of England, was chosen as an example case study to test the generic tools discussed in this study because it is a representative conurbation in United Kingdom (UK). It encompasses one of the largest metropolitan areas in UK and is made up of ten Local Authorities (Bolton, Bury, Manchester, Oldham, Rochdale, Salford, Stockport, Tameside, Trafford and Wigan). The six authorities of relevance for this study (in order of decreasing importance: Manchester, Salford, Trafford, Bury, Oldham and Tameside) have been highlighted in Fig. 3.1. The whole of Greater Manchester covers a total surface area of 1300 km^2 and is home to approximately 2.7 million individuals (White and Alarcon, 2009). Salford and Manchester form the core of the conurbation and are the most densely built-up areas in Greater Manchester. The remaining eight Local Authorities form an urban fringe around Salford and Manchester, and are considerably less urbanised.

Greater Manchester, located at North England, lies at 53°28′0″N 2°14′0″W and experiences a temperate maritime climate. It is one of the most urbanised and densely populated areas of the country. There is a mix of high density urban areas, suburbs, semi-rural and rural locations in Greater Manchester, but overwhelmingly the land use in the county is urban. It lies at an altitude of 40 m above sea level (White and Alarcon, 2009).

Due to the interconnectivity between Local Authorities, problems such as urban green space loss and flooding in one area of the conurbation will usually have a knock-on effect in the remaining local authorities (AGMA, 2008). It is through recognising this that the ten Local Authorities joined together in 2011 to form the Greater Manchester Combined Authorities (GMCA) to tackle common challenges.

Storm water runoff from impermeable surfaces has been identified by strategic flood risk assessments undertaken by local authorities (unpublished internal working documents) as one of the main flood sources in the conurbation. Conventionally, storm water runoff in Greater Manchester is dealt with using combined sewer systems. Concerns with this traditional method of dealing with storm water runoff only arose after a serious flood incident in 1998. With the turn of the century, new national policies such as the Planning Policy Guidance Note 25 on the Development and Flood Risk Management (DTLR, 2001) were released to address flooding issues. This guidance note formally introduced the use of sustainable (urban) drainage systems including permeable pavements to deal with the improved management of drainage and green spaces (DTLR, 2001; DTLR, 2011; White and Alarcon, 2009).

3.2.2. Site assessment

A total of 100 sites and corresponding catchment areas that were large enough for the retrofitting of SUDS to have a positive urban drainage impact were identified by studying Ordnance Survey and Google maps of Greater Manchester. Moreover, discussions with local authorities, United Utilities (water authority) and major private land owners regarding suitable SUDS sites were held. A map of Greater Manchester highlighting all sites visited was created using the computer software GNU Image Manipulation Program (Fig. 3.1). The main areas targeted within Greater Manchester were Salford and Manchester, the two most built-up local authorities in the conurbation. A number of sites within the inner most parts of Trafford were also visited. The purpose on focusing the study on these urban areas of Greater Manchester was to demonstrate that the implementation of SUDS even within densely built-up cities is possible (considering combined permeable pavement and tree systems).

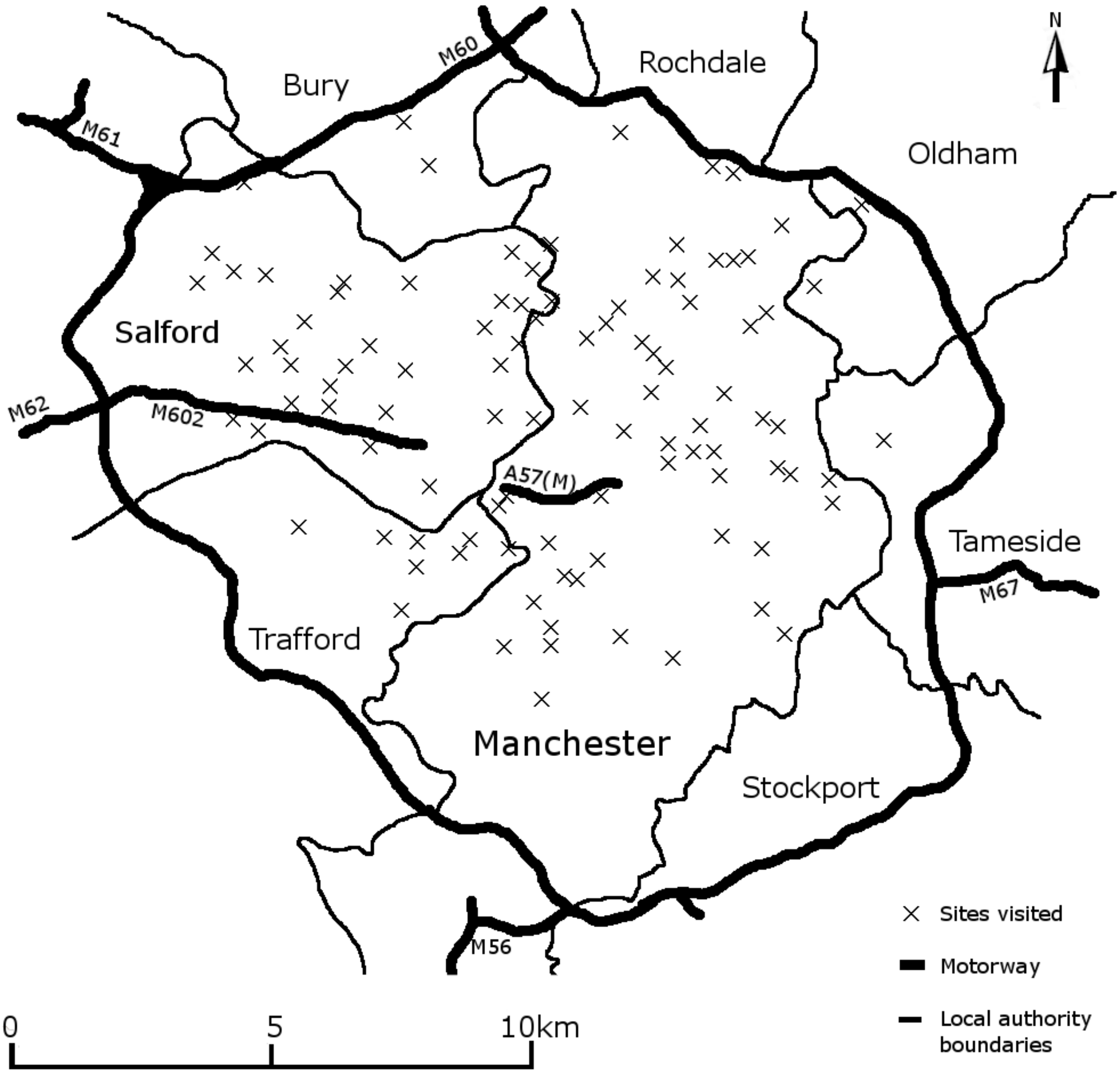


Fig. 3.1: Map indicating all potential sustainable urban drainage system (SUDS) sites assessed in Greater Manchester (example case study region).

Each potential SUDS site was assessed during a site visit by a group of civil engineering students (2 to 5 team members) to reduce subjectivity (Munoz-Pedreros, (2004)) supported by a desk study. A relative measure of certainty expressed in percentage was given to each variable to indirectly measure the reliability of the assessment. Only values higher than 50% were considered to be acceptable (see section 3.2.5).

1	**Select potential SUDS sites in case study area**	Essential
2	**Undertake site visits and note general variables**	Essential
3	**Desk study for each potential SUDS site**	Essential
4	**Determine all ecosystem service variables and associated confidence values**	Essential
5	**Decide on application of a weighting system (if appropriate) for a specific profession**	Recommended
6	**Decide on dropping variables where the confidence values are too low or undertake further field and/or desk studies**	Optional
7	**Assess the feasibility of at least the top three proposed SUDS techniques**	Recommended
8	**Compare findings to the outcomes of the traditional CIRIA and/or combined approach**	Optional

Fig. 3.2: Overview of the essential, recommended and optional steps of the new ecosystem services assessment approach for retrofitting of sustainable drainage systems (SUDS) in urban areas

The following key site information was collected and recorded using the tool during site visits:

1. General site information such as site number and name, postcode, grid reference numbers, location name, names of the inspection team members, site acceptability for SUDS systems and presence of existing SUDS techniques and trees species. Photos of the key site features were taken for each potential SUDS site and its catchment;
2. Land ownership information such as number of owners, ownership type (private or public) and estimated site value (£);

3. Proportions (%) of site classification categories including development, regeneration, retrofitting and recreation (estimated).
4. Surrounding area characteristics such as descriptions of the neighbourhood to the North, South, East and West, current and future site use, total area of the catchment (m^2), and catchment shape;
5. The location and distance (m) of the sites to the nearest sewer, storm pipe, stream, river, canal, pond, lake and sea were described by the team, if located within a reasonable distance from the catchment;
6. Estimated current and future surface permeability (%) for the land categories grass, trees, shrubs and impermeable surfaces of the proposed SUDS site and its catchment;
7. Estimated proportions (%) of current and future roof runoff for the categories: institutional, commercial, industrial, high density housing, medium density housing, low density housing and other;
8. Estimated proportions (%) of current and future road runoff for the categories: car park, motorway, primary road (or dual carriageway), A road, B road, tertiary road and others;
9. For each sub-catchment, the area (m^2) and the gradient in the two main directions having an angle of 90º to each other in the horizontal plain;
10. Hydro-geological information such as contaminated land (present or absent), soil infiltration (low, medium or high) and groundwater level (below or above 2 m depth);
11. Additional remarks regarding current drainage techniques and potential problems regarding the implementation of future SUDS techniques;
12. Finally, the SUDS technology feasibility proportion (%) (estimated).

3.2.3. Ecosystem service variable assessments

A list of ecosystem service variables and their prospective categories used in this study is provided in Table 3.1. The listed ecosystem services have been reinterpreted to make them relevant to SUDS retrofitted in urban areas and are categorised in broad agreement with TEEB (2011) and other guidance documents such as Moore and Hunt (2012). TEEB (2011) proposed a comprehensive list of ecosystem service variables of generic nature, while Moore and Hunt (2012) chose a smaller set of variables particularly adapted for SUDS such as constructed wetlands and ponds. The potentials of new quantitative and qualitative approaches to assessing ecosystem services have been explored by Busch et al. (2012).

In addition to the standard variables outlined in this section, Table 3.2 shows an overview of the proposed 17 new ecosystem service variables, which were also determined for the 100 potential SUDS sites. These variables belong to the established four ecosystem service categories of supporting, regulating, provisioning and cultural (Table 3.1).

Each ecosystem service variable is described qualitatively and quantitatively in Table 3.2 with the help of five bins (category groupings). A team of experts has to assign percentage points per variable based on comparable experience. Bin 1 always describes the characteristics of sites, which are considered to be of lowest ecosystem service value (0-20%), while bin 5 constantly identifies characteristics of sites, which are considered to be of greatest ecosystem service potential (80-100%).

Table 3.1: Universal ecosystem service categories and variables for SUDS and combined tree systems.

Category	Variable	Generic ecosystem service variable description
Supporting Services	1. Habitats for species (HS)	Urban habitats should provide everything that an animal needs to survive: food, water and shelter. Each ecosystem provides different habitats that can be essential for a species' lifecycle. Migratory species including birds and insects all depend upon different ecosystems during their movements.
	2. Maintenance of genetic diversity (MGD)	Genetic diversity (the variety of genes between and within species populations) distinguishes different breeds or races from each other, providing the basis for locally well-adapted cultivators. Some urban habitats have an exceptionally high number of species, which make them more genetically diverse than others; they are known as 'biodiversity hotspots'.
Regulating Services	3. Local climate and air quality regulation (LCAR)	Trees lower the temperature by providing shade and influence water availability (e.g., evapotranspiration). Trees and other plants also play an important role in regulating air quality by removing pollutants from the atmosphere (e.g., filtration and absorption of particulates and NO_x).
	4. Carbon sequestration and storage (CSS)	Ecosystems regulate the climate by storing greenhouse gases such as carbon dioxide through burial and sediment accretion. As trees grow, they remove carbon dioxide from the atmosphere and effectively lock it away in their tissues; thus acting as carbon stores.
	5. Moderation of extreme events (MEE)	Ecosystems and living organisms create buffers against natural disasters, thereby preventing or reducing damage from extreme weather events or natural hazards including floods, storms and landslides. Trees stabilise slopes. Flooding may be reduced through regulating runoff. Permeable pavements without a liner increase groundwater recharge.
	6. Storm runoff treatment (SRT)	Physical, chemical and biological treatment takes place within permeable pavement systems. Trees filter effluents such as storm water runoff. Through the biological activity of microorganisms in the soil and sediment, most waste is broken down; thereby pathogens (disease-causing microbes) are eliminated, and the level of nutrients and pollution is reduced. However, sediments may accumulate within permeable pavement systems.
	7. Erosion prevention and maintenance of soil fertility (EPMSF)	Soil erosion is a key factor in the process of land degradation. Tree cover provides a vital regulating service by preventing soil erosion. Soil fertility is essential for plant growth and agriculture, and well-functioning ecosystems supply soil with nutrients required to support plant growth. Established combined permeable pavement and tree systems are usually sinks for contaminants.
	8. Pollination (P)	Insects and wind pollinate plants including trees, which is essential for the development of fruits and seeds. Animal pollination is an ecosystem service mainly provided by insects but also by some birds.
	9. Biological control (BC)	Ecosystems are important for regulating pests and vector borne diseases that attack plants, animals and people. Ecosystems regulate pests and diseases through the activities of predators and parasites. Birds, flies, wasps and fungi all act as natural controls.
Provisioning Services	10. Food (F)	Food comes principally from managed urban horticulture. Fruit trees may provide food.
	11. Raw materials (RM)	Some trees deliver a great diversity of materials for construction and fuel, including wood, biofuels and plant oils that are directly derived from wild and cultivated plant species. However, most urban trees are more likely to have a high ornamental value.
	12. Fresh water (FW)	Ecosystems play a vital role in providing cities with drinking water, as they ensure the flow, storage and purification of water. Trees influence the quantity of water available locally.
	13. Medicinal resources (MR)	Some tree products may be used as traditional medicines or provide raw materials for the pharmaceutical industry.

Cultural Services	14. Recreation, and mental and physical health (RMPH)	Wildlife viewing, walking, jogging and playing sports in green spaces is a good form of physical exercise and helps people to relax. The role that green space plays in maintaining mental and physical health is increasingly becoming recognised, despite difficulties of measurement.
	15. Tourism and area value(T)	Ecosystems and biodiversity play an important role for local tourism, which in turn provides considerable economic benefits. Cultural and eco-tourism can also educate people about the importance of biological diversity. The value of properties in the area may be positively affected by the presence of an attractive permeable pavement site with trees and street furniture.
	16. Aesthetic and educational appreciation and inspiration for culture, art and design (AEAICAD)	Language, knowledge and the natural environment have been intimately related throughout human history. Biodiversity, ecosystems and (predominantly natural) landscapes have been the source of inspiration for art, culture and increasingly for science. Trees within urban green spaces may provide soothing and educational benefits, and a sense of beauty for some observers. Some attractive urban areas may also promote health and well-being.
	17. Spiritual experience and sense of place (SESP)	Some urban forms may be considered to have a religious meaning. Trees are a common element of some major religious and traditional knowledge. They can become important for creating a sense of belonging.

Table 3.2: List of new ecosystem service variables to be used for the assessment of universal retrofitting of SUDS and combined tree systems. Note that the second row indicates percentage points given to each bin category describing each variable.

Ecosystem service variable	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
	(0–20%)	(>20–40%)	(>40–60%)	(>60–80%)	(>80–100%)
1. Habitats for species (HS)	Wildlife benefits of the proposed SUDS area are very low due to an unsuitable surrounding area, but mainly due to the very impermeable surface coverage of the site.	Wildlife benefits of the proposed SUDS area are low due to a partly unsuitable surrounding area, but mainly due to the impermeable surface coverage of the site.	Wildlife benefits of the proposed SUDS area are moderate due to a partly suitable surrounding area.	Wildlife benefits of the proposed SUDS area are high due to a suitable surrounding area and due to the permeable surface coverage of site.	Wildlife benefits of the proposed SUDS area are very high due to a very suitable surrounding area and due to the highly permeable surface coverage of site.
2. Maintenance of genetic diversity (MGD)	Site is very isolated from other habitats and does not consist of a variety of ecosystems, thus can only maintain a very limited number of species; SUDS technique having a short life-span will have no effect on providing a new habitat and thus creating wider diversity.	Site is isolated from other habitats and does not consist of a variety of ecosystems, thus can only maintain a limited number of species; SUDS technique having a short life-span will have little effect on providing a new habitat and thus creating wider diversity.	Site is moderately isolated from other habitats and consists of an average variety of ecosystems, thus maintaining an average number of species; SUDS technique having a moderate life-span may have some effect on providing a new habitat and thus creating wider diversity.	Site is partly interconnected to neighbouring habitats and consists of a large variety of ecosystems, thus maintaining a sufficient number of species; SUDS technique having a long life-span will have a high impact on providing new habitats.	Site is interconnected to neighbouring habitats and consists of a very large variety of ecosystems, thus maintaining a huge number of species; SUDS technique having a long life-span will have a very high impact on providing new habitats and thus creating even wider diversities.
3. Local climate and air quality regulation (LCAR)	Areas of trees are small; open surface waters are absent.	Small areas of trees are present; open surface water may be present but not in abundance.	Moderately covered by trees, which are scattered over the area of the site, and also some open surface water is present.	Site is highly covered by dense and some mature trees, and an established surface water body is also present.	Site is entirely covered by dense mature trees, and mature surface water bodies are also present.
4. Carbon sequestration and storage (CSS)	Very small site comprising areas of a few small trees.	Small site containing small areas of mainly small trees.	Medium-seized site, which is moderately covered by trees.	Large site comprising mainly a dense coverage of trees.	Very large site, which is entirely covered by dense and mature trees.
5. Moderation of extreme events (MEE)	In the case of events such as flooding, droughts and fire, the site is totally inadequate.	In the case of events such as flooding, droughts and fire, the site is inadequate.	In the case of extreme events such as flooding, droughts and fire, the site will moderate some of these events.	In the case of extreme events such as flooding, droughts and fire, the site will moderate all of these events.	In the case of extreme events such as flooding, droughts and fire, the site will moderate all of these events very well.
6. Storm runoff treatment (SRT)	Very low potential to remove pollutants not even through physical processes.	Low potential to remove pollutants only through physical processes.	Medium potential to remove pollutants through physical processes or biodegradation.	High potential to remove pollutants through physical or chemical processes, and biodegradation; some filtration through a mature root system.	Very high potential to remove pollutants through physical and chemical processes, and biodegradation; filtration through a mature roots system.
7. Erosion prevention and maintenance of soil fertility (EPMSF)	Very low erosion prevention potential and very low likelihood of maintenance of soil fertility.	Low erosion prevention potential and/or low likelihood of maintenance of soil fertility.	Some erosion prevention potential and/or a fair likelihood of maintenance of soil fertility.	High erosion prevention potential and/or high likelihood of maintenance of soil fertility due to mature tree cover.	Very high erosion prevention potential and very high likelihood of maintenance of soil fertility due to dense and mature tree cover.

8. Pollination (P)	Site has a very low, if any, potential for the presence of any animals.	Site has a low potential for the presence of any animals.	Site has a moderate potential for the presence of animals such as insects to pollinate surrounding areas.	Site has a high potential for the presence of animals such as insects to pollinate surrounding areas.	Site has a very high potential for the presence of animals such as insects to pollinate surrounding areas.
9. Biological control (BC)	Site has no potential for the presence of predatorily animals and insects to regulate pests and diseases in the surrounding areas.	Site has a low potential for the presence of predatorily animals and insects to regulate pests and diseases in the surrounding areas.	Site has a moderate potential for the presence of predatorily animals and insects to regulate pests and diseases in the surrounding areas.	Site has a high potential for the stable presence of predatorily animals and insects to regulate pests and diseases in the surrounding areas.	Site has a very high potential for the very stable presence of predatorily animals and insects to regulate pests and diseases in the surrounding areas.
10. Food (F)	Very small and contaminated site having no or very little potential to produce food.	Small and partly contaminated site having a slight potential to produce food.	Medium-sized site having a moderate potential to produce food; presence of some fruit trees.	Large and fertile site having a high potential to produce food; presence of mature fruit trees.	Very large and fertile site having a very high potential to produce food; presence of mature fruit trees.
11. Raw materials (RM)	Very small site having no or very little potential to produce any raw materials; virtually no trees are present.	Small site having a slight potential to produce any raw materials; trees are mainly used for ornamental purposes.	Medium-sized site having moderate potential to produce raw materials; trees have the potential of being harvested.	Large site having a good potential to produce raw materials; trees are being harvested regularly.	Very large site with great potential to increase raw material production; trees are being harvested regularly.
12. Fresh water (FW)	Very low amount of surface runoff; very high pollution.	Low amount of surface runoff; high pollution.	Medium amount of surface runoff; medium pollution.	High amount of surface runoff; low pollution due to the presence of mature trees.	Very high amount of surface runoff; very low pollution due to the presence of mature and dense trees.
13. Medicinal resources (MR)	Virtually no potential for plants to be used for medicinal purposes.	Low potential for plants that can be used as medicinal resources.	Medium potential for plants that can be used as medicinal resources.	High potential for plants that can be used as medicinal resources.	Very high potential for plants that can be used as medicinal resources.
14. Recreation, and mental and physical health (RMPH)	Small site that is not safe and provides no recreational opportunities for anybody; SUDS site requires fencing in.	Small site that provides some recreational opportunities for a small group of people; SUDS site may require fencing in.	Site provides some recreational opportunities of high quality.	Large site providing ample safe and recreational opportunities of high quality for virtually everybody.	Large site providing ample safe and recreational opportunities of high quality for everybody.
15. Tourism and area value (TAV)	Site does not provide any value for local tourism; property value around the site will decrease; rundown estate.	Site does provide limited value for local tourism; property value around the site may decrease; potentially a rundown estate.	Site would attract some attention and some local visitors; property value around the site will not be affected.	Site would attract much attention and a large number of visitors from the region; increase of property value nearby.	Site would attract much attention and a large number of visitors from the wider region; high increase of property value in the area.
16. Aesthetic and educational appreciation and inspiration for culture, art and design (AEAICAD)	SUDS site does not increase the attraction of the area or provide any additional inspiration.	The area would become slightly more aesthetically pleasing, providing a slight increase in inspiration for some individuals.	The area would become more aesthetically pleasing and provides limited inspiration to a few local people.	The SUDS site would create an aesthetically pleasing area providing some inspiration to local people; potentially an education resource.	The SUDS site would create an area of outstanding beauty providing much inspiration for people with diverse backgrounds; highly valuable education resource.
17. Spiritual experience and sense of place (SESP)	Provides people with no connection to the land.	Provides a place which has a slightly warm and welcoming feeling.	Creates a site where people feel safe and secure.	The site becomes a place where people feel like they belong.	The site makes people feel connected to the area and have a sense of strong belonging.

Table 3.3: Ecosystem service variables.

Services	Number	Variable	Abbreviation
Supporting	1	*Habitat for species*	*HS*
	2	*Maintenance of genetic diversity*	*MGD*
Regulating	3	*Local climate and air quality regulation*	*LCAR*
	4	*Carbon sequestration and storage*	*CSS*
	5	*Moderation of extreme events*	*MEE*
	6	*Storm runoff treatment*	*SRT*
	7	*Erosion prevention and soil fertility*	*EPSF*
	8	*Pollination*	*P*
	9	*Biological control*	*BC*
Provisioning	10	*Food*	*F*
	11	*Raw materials*	*RM*
	12	*Fresh water*	*FW*
	13	*Medicinal resources*	*MR*
Cultural	14	*Recreation, and mental and physical health*	*RMPH*
	15	*Tourism and area value*	*TAV*
	16	*Aesthetics, education, culture and art*	*AECA*
	17	*Spiritual experience and sense of place*	*SESP*

3.2.4. Variation of each ecosystem service for each SuDS intervention

Table xx gives a general overview of how ecosystem service variables were scored with respect to each SUDS techniques. For example, under Habitat for species (HS), Ponds will score very high followed by Constructed wetlands and Water playgrounds because of their tendencies to harbour various species of plants and animals. Green roofs and Swales will score very high under Local climate and air quality regulation (LCAR) and Carbon sequestration and storage (CSS) because of their tendencies to have large amount of green plants or grasses, but will score low under Biological control (BC) and Food (F). All techniques will score very low under Medicinal resources (MR) as they are not related to providing raw materials for the pharmaceutical industry. However in some countries, some tree products may be used as traditional medicines.

Table 3.4: Variation of each ecosystem service for each SuDS technique intervention.

Ecosystem service variables	SuDS Techniques										
	Permeable pavement	Filter strip	Swale	Green roof	Pond	Constructe d wetland	Filtration trench	Soak away	Infiltration basin	Belowgrou nd storage	Water playground
1. Habitats for species (HS)	0	X	XX	XX	XXXX	XXX	X	XX	XX	0	XXX
2. Maintenance of genetic diversity (MGD)	0	0	X	XX	XXX	XXX	X	XX	X	0	XXX
3. Local climate and air quality regulation (LCAR)	X	0	XXXX	XXXX	XXX	XX	0	0	XX	0	XX
4. Carbon sequestration and storage (CSS)	0	0	XXXX	XXXX	X	XX	X	0	XX	0	X
5. Moderation of extreme events (MEE)	XXXX	XX	XXXX	XX	XXXX	XXX	XX	XX	XXX	XXX	XXX
6. Storm runoff treatment (SRT)	XXX	XX	XXXX	0	XXX	XXXX	XX	X	XXX	XXX	XX
7. Erosion prevention and maintenance of soil fertility (EPMSF)	XXXX	XX	XXXX	X	XXX	XXX	XXX	XX	XXX	XXX	X
8. Pollination (P)	0	0	X	XXX	X	X	0	0	X	0	X
9. Biological control (BC)	0	0	0	X	X	X	0	0	X	0	0
10. Food (F)	0	0	0	X	XX	0	0	0	X	0	X
11. Raw materials (RM)	X	0	X	X	0	X	0	0	X	0	0
12. Fresh water (FW)	XX	X	XX	0	0	0	X	0	0	XX	X
13. Medicinal resources (MR)	0	0	0	0	0	0	0	0	0	0	0
14. Recreation, and mental and physical health (RMPH)	X	0	X	X	XXXX	XXX	X	X	XX	0	XXXX
15. Tourism and area value (TAV)	XXX	X	X	XX	XXXX	XX	X	X	XX	0	XXXX
16. Aesthetic and educational appreciation and inspiration for culture, art and design (AEAICAD)	XXXX	X	XXX	XXX	XXXX	XX	XX	X	XXX	X	XXXX
17. Spiritual experience and sense of place (SESP)	X	0	0	X	XXX	X	0	X	XX	0	XXX

3.2.5. Uncertainties of the Rapidly Estimated Variables

Moreover, a qualified measure of certainty (Confidence levels) expressed in percentage points was given by a team of assessors based on their comparable experience to each variable to indicate the reliability of their assessment; the higher the value given, the more certain were the group of assessors. In order to determine the lowest confidence levels to be accepted in the assessment, a sensitivity analysis was carried out (see section 3.2.5). Inconsistencies were removed after discussion within the assessment group.

A weighting system specific to the needs of a particular region or stakeholder group could be introduced by providing weights for individual variables after consultation with a team of experts. For example, variables of low relevance such as medicinal resources in Greater Manchester could be assigned with a low weight of, for example, 1, while variables with a medium (e.g., recreation, and mental and physical health) or high (e.g., moderation of extreme events) relevance could be assigned with a medium (2) or high (3) weight, respectively. However, such a weighting system has not yet been introduced at this stage of the case study to keep the example simple.

3.2.6. Sensitivity Analysis

Sensitivity analysis was carried out in order to determine the optimum confidence level ranges to be considered acceptable. The results of the retrofitting SUDS techniques choices using the traditional method was used in this sensitivity analysis. The 1st, 2nd and 3rd SUDS techniques choices were worked out using all data with the following confidence level ranges (in %): 10-100, 20-100, 30-100, 40-100, 50-100, 60-100, 70-100, 80-100 and 90-100. The results which are presented in Table 3.4 and Fig. 3.3, indicate that, the results of the SUDS techniques choices for 10–100% confidence level range were quite erratic and too large. This pattern continues up till confidence levels of 40-100%

range. At confidence level ranges of 50-100 and 60-100, the fluctuations becomes fairly stabilised (Fig. 3.3). But at 80-100 and 90-100, the choices became too small. Therefore a confidence range of 50-100% seems to be a good representation of the confidence interval range, and can also be fairly be considered as a good average.

Moreso, when the Assessors indicate a confidence level higher than 50% in their accessed values, they are fairly confident in their assessments. Therefore only values with confidence levels greater than 50% were considered to be acceptable to progress to the next estimation without conducting further studies.

Table 3.5: Table indicating initial assessments of SUDS techniques choice (1st, 2nd & 3rd) options at different confidence levels for the Sensitivity Analysis.

SUDS Techniques	Choice options	Confidence Level ranges (in %)								
		10-100	**20-100**	**30-100**	**40-100**	**50-100**	**60-100**	**70-100**	**80-100**	**90-100**
PP	**PP 1**	62	50	37	32	30	28	25	19	11
	PP 2	24	15	23	18	17	17	15	10	5
	PP 3	57	55	19	15	14	12	10	8	5
	TOTAL	**143**	**120**	**79**	**65**	**61**	**57**	**50**	**37**	**21**
FS	**FS 1**	26	23	15	11	10	9	7	5	2
	FS 2	53	32	25	21	19	18	17	15	11
	FS 3	48	43	31	31	31	28	22	15	9
	TOTAL	**127**	**98**	**71**	**63**	**60**	**55**	**46**	**35**	**22**
SW	**SW 1**	12	5	2	0	0	0	0	0	0
	SW 2	34	15	10	6	5	4	4	2	2
	SW 3	35	39	27	20	18	16	12	8	6
	TOTAL	**81**	**59**	**39**	**26**	**23**	**20**	**16**	**10**	**8**
GR	**GR 1**	17	8	5	0	0	0	0	0	0
	GR 2	29	12	5	5	1	0	0	0	0
	GR 3	44	23	20	12	11	8	5	5	4
	TOTAL	**90**	**43**	**30**	**17**	**12**	**8**	**5**	**5**	**4**
P	**P 1**	52	41	27	20	20	17	15	11	10
	P 2	26	29	20	16	14	13	13	10	5
	P 3	33	21	15	15	14	11	9	9	7
	TOTAL	**111**	**91**	**62**	**51**	**48**	**41**	**37**	**30**	**22**
IB	**IB 1**	15	7	0	0	0	0	0	0	0
	IB 2	36	27	15	7	5	5	5	5	5
	IB 3	35	22	21	14	13	13	13	13	13
	TOTAL	**86**	**56**	**36**	**21**	**18**	**18**	**18**	**18**	**18**
SO	**SO 1**	76	75	69	57	54	50	49	37	25
	SO 2	51	42	30	29	27	25	21	19	15
	SO 3	25	26	20	12	11	7	7	5	6
	TOTAL	**152**	**143**	**119**	**98**	**92**	**82**	**77**	**61**	**46**
WL	**WL 1**	22	17	10	9	8	8	5	5	1
	WL 2	18	10	10	5	4	4	2	0	3
	WL 3	38	33	24	13	14	12	10	10	5
	TOTAL	**78**	**60**	**44**	**27**	**26**	**24**	**17**	**15**	**9**
US	**US 1**	51	44	37	32	32	32	30	25	19
	US 2	35	23	21	14	13	10	10	7	5
	US 3	43	31	22	10	8	8	5	8	4
	TOTAL	**129**	**98**	**80**	**56**	**53**	**50**	**45**	**40**	**28**
WP	**WP 1**	26	20	7	6	1	1	0	0	0
	WP 2	25	15	15	8	5	5	4	2	2
	WP 3	25	25	7	6	1	1	1	0	0
	TOTAL	**76**	**60**	**29**	**20**	**7**	**7**	**5**	**2**	**2**
IT	**IT 1**	39	27	25	22	21	21	13	15	9
	IT 2	45	47	39	33	26	26	19	15	11
	IT 3	51	46	40	30	24	24	20	20	15
	TOTAL	**135**	**120**	**104**	**85**	**71**	**71**	**52**	**50**	**35**

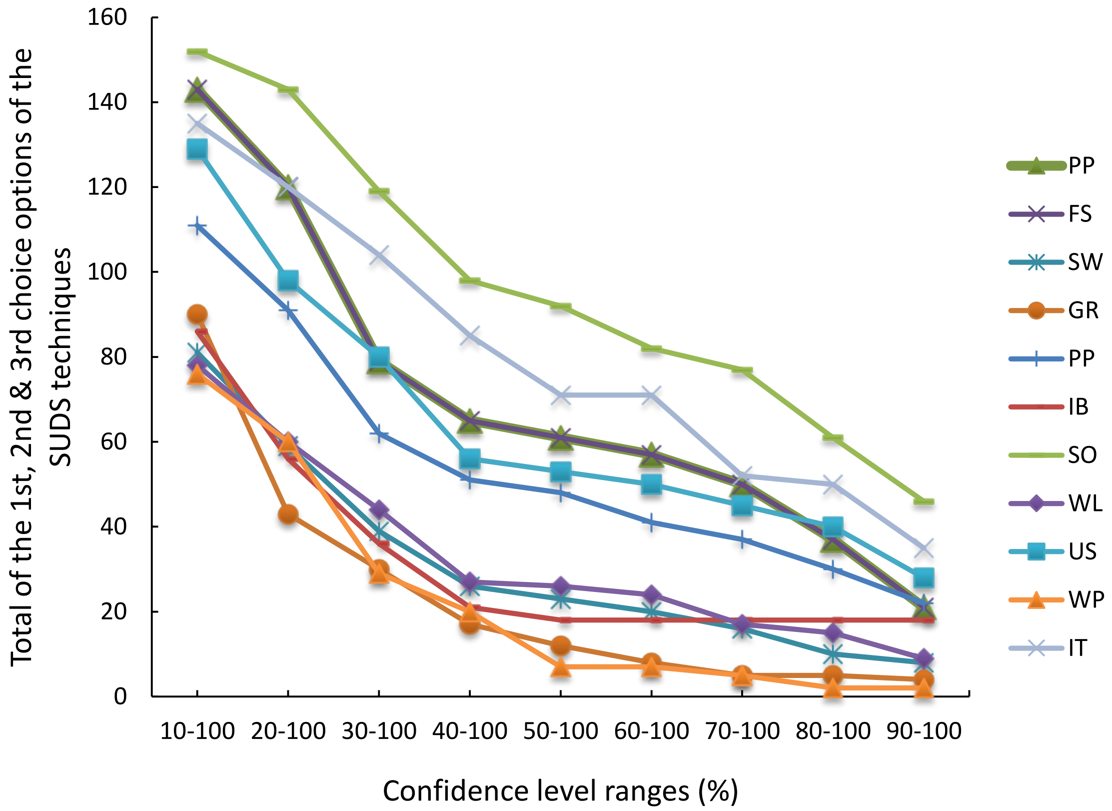


Fig. 3.3: Sensitivity Analysis of the confidence levels using the total (1st, 2nd & 3rd) choices of the SUDS techniques

3.2.7. Determination of sustainable drainage system techniques with traditional 'community and environment' variables

The site assessment was inspired by the SUDS Decision Support Key and the SUDS Decision Support Matrix developed for the Glasgow and Edinburgh SUDS retrofitting studies (Scholz, 2006; Scholz et al., 2006). All corresponding variables characterising the site were determined using these tools. However, the method used to determine which SUDS technique is likely to be most suitable for a particular site, under the traditional 'community and environmental' variables, was based on the expert tool published by CIRIA (2004).

The guideline C609 (CIRIA, 2004) basis the selection of a SUDS technique on a number of criteria related to hydrology, land use, physical site features, community and environment; and economics and maintenance. The criteria have been adapted from a technical report previously authored by Ellis et al. (2003). Each SUDS technique is scored according to each criterion from 1 to 5 where 1 refers to a SUDS technique being very unsuitable, and 5 signifies a SUDS technique being very suitable for that particular criterion. Where 0 is awarded, it indicates that the SUDS techniques in question is not relevant (not suitable) or cannot be applied in that case. The scores were then tallied up, and the SUDS technique obtaining the highest sum of scores was considered to be most suitable for that particular site. The minimum and maximum overall score for all criteria were 0 and 25, respectively.

For the purpose of this section, use is only made of the criteria falling under the category 'community and environment', which comprises the traditional variables safety, pond premium, aesthetics, wildlife habitat and acceptance, as explained below. Eliminating the other categories that do not directly relate to ecosystem services introduces bias in the overall assessment, but this was seen as acceptable for the purpose of this study, which focused only on categories of interest to ecosystem services.

- Safety - can the SUDS technique pose any danger to individuals
- Water Premium - can the SUDS technique raise the cost of property in the area
- Aesthetics - can the SUDS technique improve the visual aesthetics of the area
- Acceptance - will the local community accept the implementation of the SUDS technique
- Habitat - Can the SUDS technique improve the ecological impact of wildlife with in the wider area

The above criteria, definitions and guidance were used to assess the suitability of each SUDS site under the traditional ‘community and environment’ variable.

<u>Calculations:</u>

The maximum points obtainable for each technique under Traditional ‘community and environment approach = 25.

For ease of comparison between approaches, scores were converted to percentages, for example, where a site scored 3, 2, 4, 1 and 3 for safety, water premium, aesthetics, habitats and acceptance respectively, the Total score = 13.

Conversion to percentage = 13/25 x 100% = 52%

3.2.8. Determination of sustainable drainage system techniques with new ecosystem service variables

Table 3.2 was used to determine numerical values for the new ecosystem service variables, taking into account the generic ecosystem service variable descriptions in Table 3.1. It has to be noted that the variable medicinal resources (MR) was not really applicable for the selected example case study (Table 3.3). Points were awarded for each ecosystem variable from 1 to 5 just as in the traditional ‘community and environment’ approach, where 1 represents very poor/very low, and 5 represents very good/very high.

<u>Calculations:</u>

Since there are 17 ecosystem service variables, as outlined in Tables 3.1, 3.2 & 3.3, maximum possible score for a technique is 85.

For ease of comparison with other approaches, the Total score is converted to percentages by using (Total score)/85 x 100%.

A comparison between a site assessment based on the community and environment variables with the new ecosystem service variables was performed. They were also compared with a combination of both approaches. Considering that there are 17 variables in ‘ecosystem service’ approach, 5 variables in ‘community and environment’ approach, and 7 variables in ‘combined’ approach, it became necessary to convert their sum totals to percentages for ease of comparison.

3.2.9. Determination of sustainable drainage technique using the combination of the traditional and new approach

This section describes the last assessment method, which is a combination of the traditional and new approach by replacing the traditional criteria ‘aesthetic’ and ‘wildlife habitat’ with the four ecosystem service categories (not the 17 variables) discussed in section 3.2.3. These two traditional criteria are included in the new ecosystem service assessment. Thus the SUDS techniques are scored according to the following criteria: safety, water premium and acceptance as well as provisioning, regulating, supporting, and cultural services. The same scoring system applied above was adopted during the re-assessment of evaluating which SUDS technique is likely to be most appropriate for a particular site. Only those techniques that were most suitable (i.e. first preferences) for particular sites were subsequently recommended to the local authorities, United Utilities and private land owners for implementation.

Calculations:

For the combined approach, there are 7 variables: safety, water premium, acceptance, provisioning, supporting, regulating, and cultural services. There were maximum of 5 points per variable totalling 35 per technique per site.

Scored points are converted to 100 % by using (Total points)/35 x 100%.

3.2.10. Tree determinations

Areas at sites suitable for retrofitting of SUDS techniques including permeable pavement systems were determined. This section of assessment focuses on sites where mature trees were already present in close proximity (within 10 m) to the proposed permeable pavement system. At this stage, no restrictions were made regarding tree species and its current or projected growth characteristics, and no assumptions were made regarding environmental interactions between any pavement system and whichever tree.

Trees with a stem diameter of more than 10 cm measured at breast height (1.5 m above ground level) were determined for all case study sites in Greater Manchester in autumn 2012. Trees were identified by assessing the overall shape, leaves, bark, buds and flowers (predominantly unavailable). Only healthy trees with a good survival likelihood that were located within a strip of 10 m surrounding the site where permeable pavements could be retrofitted were assessed using a very wide range of standard tree determination guides (e.g., Woodland Trust (2012)) and expert judgement.

3.3. ASSIGNING WEIGHTING SYSTEMS FOR DIFFERENT PROFESSIONS

This section describes how a weighting system was introduced to improve the preferences in estimations from different professions. It also described the learning process of estimation.

3.3.1. Questionnaire

A questionnaire addressing the issue of *aesthetics, land cost, land size*, *habitat for species* and *safety* was developed and administered to students of Engineering, Ecology and Social Science. Questionnaires are adopted in this study due to its suitability. It is more preferred over other methods of obtaining data, like interviews, because it can reach a wider audience through the internet, subjects can respond at their convenience, give a more thoughtful opinions or assessment because they have more time to reflect on the questions (Burns and Bush, 2003; Phellas, Bloch and Seale, 2011; Zohrabi, 2013;). Questionnaires are also more cost effective. Although, it is only recommended where the responders need little or no explanations. For this research, wider audience and some targeted professions are required. Therefore, Bristol Online Survey Programme was used to administer the same questionnaire to the general public of different professions using pictures of sample sites. A copy of the survey is given in Appendix B.

3.3.2. Evaluation of the Variability of Estimated Variables and Learning Process of Estimation

The approach for evaluating the variability of the randomly selected estimated example variables *aesthetics* (Figure 3.3), *land cost*, *land size*, *habitat for species* (Figure 3.4) and *safety* is outlined in this section. Furthermore, the learning process of estimation undertaken by a relevant civil engineering student cohort example is explained with the help of a three-stage questionnaire survey based on a PowerPoint presentation.

For each variable tested, six corresponding relevant pictures representing virtually the whole numerical spectrum (*i.e.*, very low to very high values; e.g., Figure 3.3) of possible answers were selected for the questionnaire. The pictures were taken from actual case study sites in Greater Manchester, and did not contain any misleading or irrelevant information such as distracting objects of random occurrence (e.g., an ice cream van or a pedestrian) in the foreground. Figures 3.3 and 3.4 show the pictures for the variables 'aesthetics' and 'habitat for species' respectively, as examples to illustrate the approach.

(A)

(B)

(C)

(D)

(E)

(F)

Fig. 3.4: The relative assessment values for the variable *Aesthetics* (%). The values in ascending order (ie. from ugly to beautiful) based on drainage engineering expertise are: (E) 30%, (F) 43%, (B) 49%, (D) 62%, (C) 74%, and (A) 82%. All photographs were taken by Vincent Uzomah and Nathan Somerset in 2012 and 2013 (The University of Salford).

(A)

(B)

(C)

(D)

(E)

(F)

Fig. 3.5: Relative ranking values for the variable *habitat for species* (%). Ascending order (*i.e.*, from highly inadequate to highly adequate habitat) based on the Civil Engineering expertise: (**B**) 9%; (**E**) 23%; (**F**) 45%; (**A**) 62%; (**C**) 70%; and (**D**) 82%. All photographs were taken by Vincent Uzomah and Nathan Somerset in 2012 and 2013 (The University of Salford).

A mixture of 51 full-time BSc, BEng and MEng civil engineering students, who were broadly familiar with the overall case study area and studying water resources technology in their third year at The University of Salford, were asked on 19 March 2013 to assign values to each picture associated with a particular variable.

The questionnaire was split into three different stages to test progressive learning. For each stage, the same pictures had to be assessed. However, the order was changed at random. Approximately 15 seconds were allocated for each picture. At Stage 1, students had to assign values that they had to benchmark against their personal perception. They had to make reasonable assumptions about what is a low or high value for a particular variable. In comparison, at Stage 2, students were aware of the range of possible scenarios for each variable, and had the opportunity to refine their first choices purely based on their memory. In the third and final stage, all pictures associated with a particular variable were shown at the same time. Direct picture comparisons and value readjustments were possible.

Each mean score per picture provided by the student cohort was compared to a target score, which was determined by a selected civil engineering research team based on professional drainage engineering perception (e.g., Figure 3.3). The target score is also subjective (expert opinion) and should therefore only be seen as a guideline.

3.3.2. Comparison of Variability with Other Cohorts

The variables *aesthetics*, *land cost*, *habitat for species* and *safety*, which were estimated in Section 3.3.1 by civil engineers, were also approximated by ecologists and social scientists for comparison. On 3 May 2013, 42 undergraduate students studying ecology at The University of Salford were tested. Furthermore, 31 undergraduate social science students were questioned at the same university on 1 May 2013. The same methodology as presented in Section 3.3.1 was applied. However, Stage 2 of the learning process was omitted.

3.3.3. The Broad Professions

The variables *aesthetics, land cost, habitat for species* and *safety* were also estimated by 54 randomly chosen members of the general public between 26 June and 25 July 2013, using Bristol Online Survey. However, only Stage 3 (see Section 3.3.1) was applied in Bristol Online survey because of its simplicity; *i.e.*, all subjects were only presented with six pictures per variable in random order on a single sheet (see Appendix E). The questionnaire survey can be found on the web (Uzomah and Almuktar, 2013). The questionnaire remained live at least until 25 December 2013. In addition to the Bristol Online Survey, 127 surveys, similar to the Online Survey were also administered physically through meetings and conferences between June and December 2013.

The broad profession sample comprised subjects with the following backgrounds or professions: unidentified students (10%), civil engineering students (10%), engineers (33%), ecology students (0%), ecologists (12%), social science students (0%); developers (2%), planners (2%) and others (31%). Engineers and students were overrepresented in this sample. In contrast, members of the public with a below-average education were underrepresented.

3.3.4. Decision Support Tool for the Different Professions

This section outlines the methodology for the development of a decision support tool for SUDS retrofitting taking into account the perspectives of drainage engineers, developers, ecologists, planners, social scientists and the general public as defined elsewhere (Blockley, 2005). A weighting system specific to the needs of a particular stakeholder group was introduced by providing weights for individual variables (Table 3.6) based on the outcome of the initial analysis of the surveys and after consultation with different teams of academics representing different professions (drainage engineer, developer, ecologist, planner and social scientist) within The University of Salford.

Variables of low relevance for a drainage engineer such as *MR* (see Table 3.3) in Greater Manchester were assigned with a low weight, while variables with a medium (e.g., *RMPH*) or high (e.g., *MEE*) relevance were assigned with a medium or high weight, respectively. Table 3.6 proposes weights from the viewpoint of different professionals (drainage engineer, developer, ecologist, planner, social scientist and the general public). A simple weighting system with only three categories (1, low; 2, normal; 3, high) has been proposed to keep the case study example simple. A maximum weight of 3 signifies that one variable is three times more important than a variable scoring only 1. However, as a decision support tool, it may be possible, if the assessor wishes, to replace the proposed system with a more differentiated weighting system based on, for example, ten categories. Depending on the case study, location and associated boundary conditions, end-users of the proposed tool may wish to select different weights, which will subsequently impact on the results. It is up the group of experts to decide if a weighting scale should be used and what weights may be appropriate for a particular case study. However, transparency in decision-making is essential.

Table 3.6: Proposed weights as a function of user preference based on professional background

Category of service	Variable	Weights				
		Drainage engineer	Developer	Ecologist	Planner	Social scientist
Traditional assessment approach (CIRIA, 2004)						
	Safety	3	3	1	3	3
	Pond premium	1	3	3	2	2
	Aesthetics	1	3	1	3	2
	Wildlife habitat	1	1	3	2	2
	Acceptance	3	3	1	3	3
New ecosystem services approach (in Table 3.3)						
Supporting	1. Habitats for species (HS)	1	1	3	2	2
	2. Maintenance of genetic diversity (MGD)	1	1	3	1	1
Regulating	3. Local climate and air quality regulation (LCAR)	1	1	3	2	3
	4. Carbon sequestration and storage (CSS)	1	1	3	1	1
	5. Moderation of extreme events (MEE)	3	3	2	3	2
	6. Storm runoff treatment (SRT)	3	2	2	2	2
	7. Erosion prevention and soil fertility (EPSF)	2	2	2	2	2
	8. Pollination (P)	1	1	3	1	1
	9. Biological control (BC)	1	1	3	2	2
Provisioning	10. Food (F)	1	1	1	1	2
	11. Raw materials (RM)	1	1	1	1	2
	12. Fresh water (FW)	3	1	2	2	2
	13. Medicinal resources (MR)	1	1	1	1	2
Cultural	14. Recreation, and mental and physical health (RMPH)	2	2	1	2	3
	15. Tourism and area value (TAV)	1	3	1	2	3
	16. Aesthetics, education, culture and art (AECA)	1	2	1	2	3
	17. Spiritual experience and sense of place (SESP)	1	2	1	2	3
Combined approach						
	Safety	3	3	1	3	3
	Pond premium	1	3	3	2	2
	Acceptance	3	3	1	3	3
	Supporting services	1	1	3	2	2
	Regulating services	3	2	3	2	2
	Provisioning services	1	1	1	1	2
	Cultural services	1	2	1	2	3

3.3.5. Data Analysis

Microsoft Excel (Microsoft, 2013) was used for data storage and the general data analysis. The non-parametric Mann-Whitney U-test was computed using IBM SPSS

Statistics Version 20 (IBM, 2013) and used to compare the medians of two (unmatched) independent samples. This was required because virtually all sample data were not normally distributed, so that an analysis of variance could not be applied.

Table 3.7 below presents some of the Normality Tests of the data for the different professions. Kilmogorov-Smirnov and Shapiro-Wilk in SPSS were used to determine the normality of the data. The data were not normally distributed because the sig. in Shapiro-Wilk for all the pictures (A to F) are less than 0.05 (Table 3.7) (IBM, 2013).

Table 3.7. Table showing some results of the Normality Tests for the questionnaire data from the different professions. Where the sig. of the Shapiro-Wilk is less than 0.05, the dta is not normally distributed.

Tests of Normality for Ecologists (Habitat for species)

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
A	.155	42	.013	.935	42	.019
B	.282	42	.000	.848	42	.000
C	.146	42	.024	.928	42	.011
D	.249	42	.000	.787	42	.000
E	.226	42	.000	.806	42	.000
F	.221	42	.000	.768	42	.000

a. Lilliefors Significance Correction

Tests of Normality for Social Scientists (Safety)

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
A	.122	36	.013	.925	36	.018
B	.117	36	.010*	.927	36	.001
C	.202	36	.001	.909	36	.006
D	.161	36	.019	.917	36	.010
E	.149	36	.043	.932	36	.028
F	.213	36	.000	.845	36	.000

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Tests of Normality for Civil Engineering Students (Aesthetics)

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
A	.142	51	.011	.918	51	.002
B	.135	51	.002*	.963	51	.001
C	.150	51	.006	.974	51	.006
D	.134	51	.022	.969	51	.003
E	.122	51	.003*	.949	51	.028
F	.170	51	.001	.922	51	.003

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Tests of Normality for the Broad Professionals (Land cost)

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
A	.180	104	.000	.838	104	.000
B	.125	104	.000	.966	104	.009
C	.135	104	.000	.961	104	.004
D	.118	104	.001	.974	104	.038
E	.140	104	.000	.930	104	.000
F	.211	104	.000	.875	104	.000

a. Lilliefors Significance Correction

3.4. ASSESSMENT OF TREE DAMAGE TO STRUCTURES

3.4.1. The Sites

A total of 100 new sites were randomly selected in Greater Manchester area using ArcGIS software, Google Earth maps and tools (Fig. 3.5 and 3.6). These sites were different from the former SUDS retrofitting sites. The selection of the sites was restricted to a radius of about 15 km from the Manchester and Salford city centres since they are the only cities in Greater Manchester, and also having the highest development in the borough. Dots were randomly placed on a plain Google map but more concentrated around major cities (Manchester and Salford) as the targets were for trees existing alongside development structures. A representative of 100 m x 100 m square was drawn on each selected site to form a boundary for the tree assessments (See Fig. 3.5 and Appendix D). The X and Y coordinates, grid reference, longitude, latitude, and post codes of all the sites were determined (See Appendix C). The sites information including the drawn boundaries and post codes were saved on portable devices such as laptops, smart phones and electronic tablets for easy assessments on the sites.

Greater Manchester is located at North England, with a population of about 2,682,500 (as at 2011 UK census), and comprises of ten metropolitan boroughs: Bolton, Bury, Oldham, Rochdale, Stockport, Tameside, Trafford, Wigan, and the Cities of Manchester and Salford. It is one of the most urbanised and densely populated areas of the country. There is a mix of high density urban areas, suburbs, semi-rural and rural locations in Greater Manchester, but overwhelmingly the land use in the county is urban. It lies at an altitude of 40 m above sea level.

Fig. 3.6: An example site (site 5) in Greater Manchester for the assessment of tree damage with the 100 m x 100 m mark drawn to demarcate boundaries.

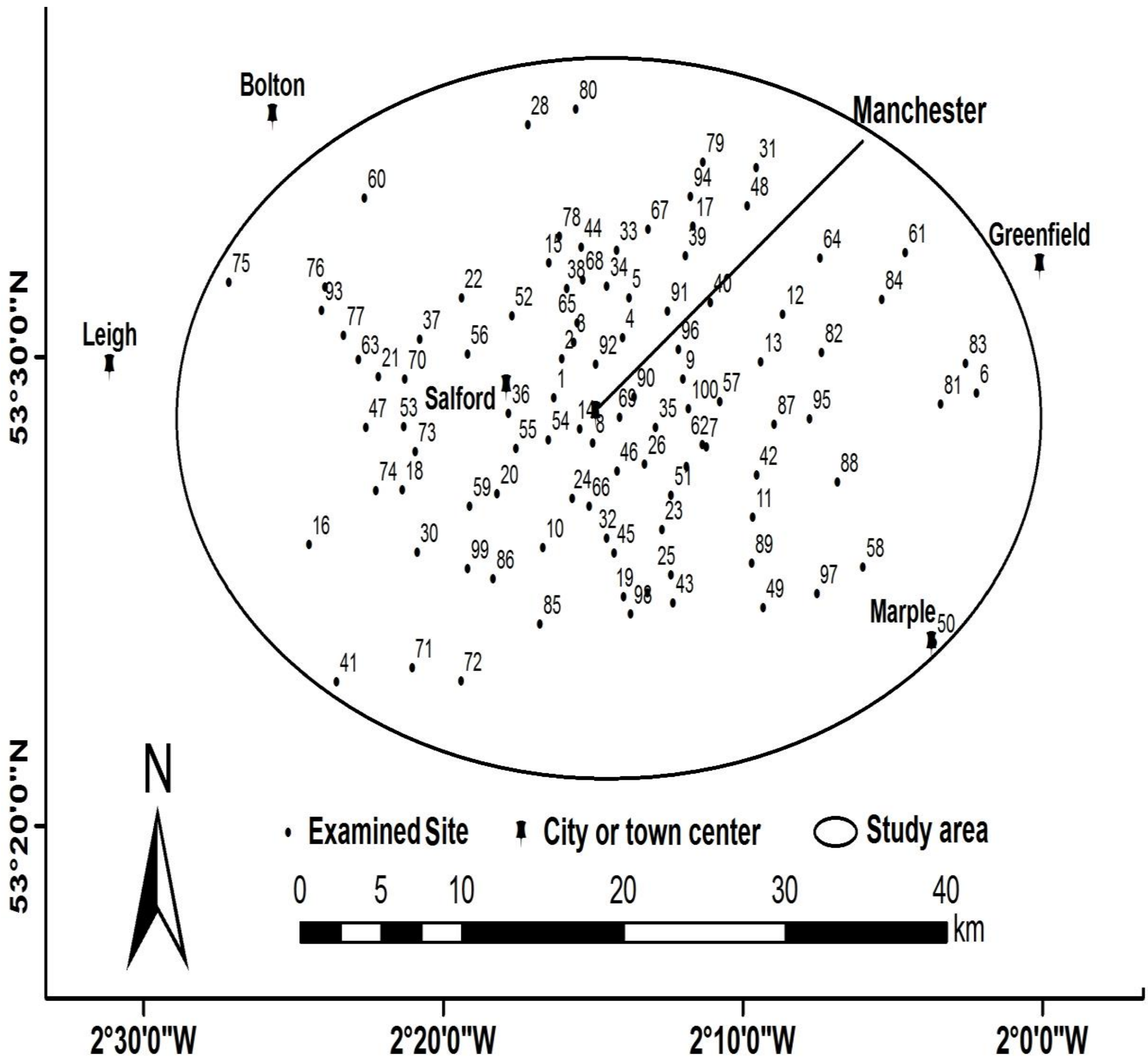


Fig. 3.7: A map of Greater Manchester highlighting the 100 sites for the tree damage assessment. (Please note that these sites are different from the SUDS assessment sites).

3.4.2. Tree Damage Data Collection

A data collection spreadsheet was developed that will enable the entry of the following parameters: site number, tree number, tree species, common name and genus, tree diameter at breast height (DBH) (1.5 m from ground level), estimated tree height, estimated tree crown diameter, structures near the tree, distance of structures from the tree, type of damage to structures and their severity (if any), and spaces for remarks. Data collections were carried out in the Spring/Summer of 2013 and 2014. Summer periods were chosen because, at these periods, trees have their full leaves, which makes tree identifications and crown spread determinations easier.

Each of the 100 sites was visited for tree damage assessment. All trees that fall within the marked 100 m x 100 m boundary with DBH greater than 10 cm were assessed (see Fig. 3.5 and Appendix D), except where a site is inaccessible for a valid reason. Sites that fell within restricted (private) access areas were not assessed and were marked as inaccessible sites. Other sites that were not assessed include sites with no trees at all, or sites where all the trees were less than 10 cm DBH.

To reduce bias, uncertainty in estimations and error in tree identification, sites were visited and assessed by at least 2-5 people, and with different types of tree identification guides. Pictures of assessed trees were taken from different possible directions (Fig. 3.7). Tree species were identified through the collective agreement of all assessors. Where agreements on tree species identification cannot be reached, the leaves of the tree together with its twigs and the pictures were taken to Ecology professionals for a final opinion.

Tree no. 10.1 (Tree 1, Site 10)

Tree no. 10.2 (Tree 2, Site 10)

Fig. 3.8: An example photo of a tree that has damaged the road, kerbs and the side walk (impermeable pavement). Note that the both the road and the impermeable pavements have been repaired (Tree 1 site 10). Photos were taken by Vincent Uzomah.

3.4.3. Tree damage Assessment

Each tree was given a number reflecting the site in which it is located. The DBH was calculated by measuring the circumference at breast height using tape measure, and dividing the value by pie (π). Trees less than 10 cm in diameter were not regarded as they are considered too young to affect any present damage. Tree heights were estimated using a method based on 'goniometry' and also comparing the tree height with nearby structures such as houses, electric and telephone poles. Goniometry involves walking away from the base of the trunk until you see the tree's top from an angle of 45° (which you can check using your arm). The height of the tree roughly equates to the distance from the tree to where the observer is standing plus his or her eye height from the ground (Monumental trees, 2015).

The structures that were considered in the assessment are (a) permeable pavements; (b) impermeable pavements; (c) kerbs and roads; (d) retaining walls; (e) buildings; and (f) footpaths. The foot path structure refers to a walkway though areas such as parks, and excludes road side-walks. The damage that were taken into account are (a) lifting-up of structures; (b) disjointing of structures by roots; (c) sinking in (depression) of structures; and (d) cracking up of structures.

The severity of damage was determined by assigning numbers between 1 and 5, where 1 represents an emerging damage at an early stage, 2 represents an emerging damage that is gradually advancing, 3 represents a well-established damage, 4 represents an advanced damage, e.g. pavements completely separated or kerbs completely disjointed, and 5 represents a well advanced damage that has become a safety hazard to users or that requires an immediate attention or that has been already repaired.

For the purpose of analysis, scores of 1 were later referred to as ‘light damage’, 2 to 3 as ‘moderate damage’, and 4 to 5 as ‘severe damage’.

In order to make sure that tree species that have a good spread in Greater Manchester are well reflected in the analysis, and also that recorded damage were actually caused by trees and not by other reasons such as soil settlements, the following criteria were applied:

(1) Tree species that had less than 10 occurrences in total were not included in the analysis;
(2) Tree species that occurred in less than five different sites were also discarded.
(3) All damage classed as 'light' were also not included in the detailed analysis.

For the analysis of structural damage, only the structures with at least ten damage from any tree were considered. This is to ensure that only structures with adequate tree relationship are represented. Closeness of a tree to a structure was limited to 10 m. This was to give room for the root protection area (RPA) (BSI, 2013), which for most available trees, fell within 9 m.

3.4.4. Tree Age Estimations

Where necessary, the age of Silver birch was calculated using the formula: Age = $4.17 + 0.767d$, which was developed by Tkaczyk and Tomusiak (2013) for Silver Birch, where d = DBH of Silver Birch in cm. However, there are little or no known expressions for determining age of other trees other than using destructive methods.

3.5. ASSESSMENT OF PUBLIC PERCEPTIONS AND AESTHETICS FOR THE TREES OF MOST CONCERNS.

3.5.1. The Arboretum's Tree Data Collection

After the preliminary assessment (which covered 25 out of 100 sites) of the tree damage to structures, and the investigation of tree occurrence data at the SUDS retrofitting sites in Greater Manchester, a list was prepared showing the 12 most common trees that also have high potential for causing structural damage to both SUDS and road structures. There was, therefore, the need to study the public perception and acceptability of these trees and the potential values associated with them.

In order to obtain images of these trees that grew under optimum conditions with no obstructions from any structures, pictures of trees taken from the National Arboretum, Westonbirt, Gloucestershire, UK, were used for the public perception assessment. The Westonbert Arboretum is a historic, Victorian landscape where internationally important tree and shrub collection is managed by the England's Forestry Commission. There are 14,902 labelled trees and about 2,500 species of trees at Westonbirt Arboretum that came from Britain, China, North America, Japan, Chile and other temperate climates. It consists of 17 miles (27 km) of accessible paths, and has an area of approximately 600 acres (2.4 km^2) (Forestry Commission, 2015).

Visits for the assessments at Westonbirt were made both in spring (May) and autumn (October and November) of 2013 to compare the public's perception and values for those trees, as these are the seasons when tree appearances considerably change.

The position and site location for each of the 12 trees were mapped out on the Westonbirt map prior to the visits. Photos and videos of the trees were taken. The positions of the photographers were marked for each tree photographed; the zooms and resolutions of the cameras were also noted. The photographs of each of these trees were taken from the same positions in each of the seasons (Fig. 3.8). Also, videos showing the 360^o circumferential view of the trees were made during the visits.

3.5.2. The Arboretum's Tree Assessment

Twenty four (24) pictures of the trees, comprising of a spring picture and an autumn picture of each of the 12 trees, were used to prepare Microsoft PowerPoint presentations. Each picture was presented in full, one at a time to an audience, for 2 minutes, in no particular order so that each participant would have a chance of seeing a picture (one for spring and one for autumn) of each of the 12 trees twice. The purpose was to compare the perception of tree species with each other, and to assess the difference that seasons make in the perceptions of the same tree.

This presentation was given 140 students comprising mainly of first-year, second-year, third-year and fourth-year students of BSc, BEng, MEng courses in Civil Engineering, and also of Civil and Architectural Engineering. 37 students from Medicine, Human biology, Biochemistry and Dentistry also took part in the survey. The participants were requested to rank the appearance of the trees according to how appealing the trees look and whether they would like to have them near where they live. The students had to assign values from 1 to 100; lower values represent rejection and low appeal, while higher values indicate acceptance and high appeal.

In addition to pictures, videos of the trees were also incorporated alongside the PowerPoint presentations to give participants a better 3-dimensional view. The videos showed 360^{o} view of the full height of the trees.

Large-leaved lime in Spring

Large-leaved lime in Autumn

Common Beech in Spring

Common Beech in Autumn

Fig. 3.9: Examples of images of trees in spring and their corresponding images in autumn (taken at the Arboretum), used in the assessment of public perception and acceptance of 12 most common trees in Greater Manchester. Photos were taken by Vincent Uzomah.

3.6. Chapter Summary

The three different stages of this research work were explained in this chapter.

Stage 1 explains the development and modification of the decision support tool, and how it was used to assess SUDS retrofitting options using the three different approaches. The new 17 ecosystem service variables and their quantitative values using defined bins were outlined. Then the 5 variables of the traditional 'community and environment' approach and the 7 variables of the 'combine' approach were also given.

Stage 2 explains how weighting systems were introduced that reflected the different profession of stakeholders.

Stage 3 explains how further work was carried out on trees and permeable pavements when it was found out that permeable pavements were scoring high in preference to most SUDS techniques. This stage focused on assessing tree damage to structures such as: permeable pavements, impermeable pavements, kerbs, roads, retaining walls and buildings. This stage of work was necessary so as to establish which type of tree species are best suited to retrofitting of permeable pavements in the presence of other structures.

It also explains how a study on public acceptance of the tree species was carried out using the National Arboretum, so as to compare damage by trees and aesthetics from trees.

CHAPTER 4

DECISION SUPPORT TOOL FOR SUDS RETROFITTING: RESULTS AND DISCUSSION

4.1. Overview

This chapter discusses the initial assessment of the Decision Support tool for retrofitting sustainable drainage systems. It compares the three assessment approaches with one another: Community and Environment (The traditional or CIRIA), Ecosystem service, and The Combined approaches. It also analyses the approaches as to their suitability for being used to choose the most appropriate SUDS techniques.

The results and discussions in this chapter, including figures and tables, already formed part of the paper published from this research as indicated in paper no. 1 on page viii.

4.2. General Overview of the Site Assessment Outcomes

Only 16% of the example case study sites were existing SUDS sites. Most of these were of poor design with low ecosystem service value. There was a clear need for introducing SUDS to improve drainage in all cases, which is realistic, because most sites are owned by the public hand (52% public, 23% private and public, and 25% private) and not multiple private owners. The estimated site values were relatively low (26% low, 32% low to medium, 29% medium, 11% medium to high and 2% high), which supports SUDS implementation due to low competition with private investors.

Most sites were not just potential retrofitting sites but a combination of different potential types: combination of at least two categories (81%), retrofitting only (15%), development only (2%), regeneration only (2%) and recreation only (0%). This was reflected in the current site use, which was dominated by public or at least publicly accessible areas: park (41%), car park (33%), institutional building (12%), disused land

(8%) and field (6%). This scenario is unlikely to change in the near future according to consultations with the site owner and local authority (park (56%), car park (32%), institutional building (12%), disused land (0%) and field (0%)). The trend towards converting 'empty spaces' into parks is a positive development.

The current site permeability assessment indicated that 21 sites were fully paved (usually with tarmac). The remaining 79 sites were unpaved. Permeable pavements are suitable to replace 20 and 46 currently paved and unpaved sites, respectively, in the future. The sites that are currently unpaved and where permeable pavement would be suitable would drain the precipitation covering the paved area. The retrofitted permeable pavements would function as future car parks and pavements.

The catchment size (in 1000 m^2) of most sites was relatively small (<25 (29%), 25 to <50 (32%), 50 to <100 (20%), 100 to <150 (6%) and ≥150 (13%)), indicating that SUDS may only make a minor contribution towards resolving the urban drainage problem. The vast majority of potential SUDS sites (63%) had only sewers, while the remaining sites had both sewers and storm pipes (37%). Additional catchment drainage options were dominated by sewers: sewer (100%), storm pipe (2%), stream (0%), river (11%), canal (21%), pond (6%) and lake (2%). The low proportion of natural and flowing receiving watercourses makes the introduction of large-scale infiltration techniques attractive. However, infiltration techniques, generally, did not score high on ecosystem service variables compared with the traditional community and environment variables.

The current site permeability (%) was high: <20 (24%), 20 to <40 (2%), 40 to <60 (1%), 60 to <80 (3%) and ≥80 (70%). In contrast, the current catchment permeability (%) was low: <20 (21%), 20 to <40 (13%), 40 to <60 (17%), 60 to <80 (30%) and ≥80 (19%), indicating a good potential for infiltration devices.

The present runoff area proportions were as follows: roads (48%), mainly roofs and roads (11%), and mainly roofs (41%). Despite the high proportion of roofs, the slopes (%) of current sites were rather flat: <0.5 (20%), 0.5 to <1.5% (53%), 1.5 to <2.5 (10%), 2.5 to <3.5 (7%) and ≥3.5 (10%). This is likely to lead to reduced levelling costs when retrofitting permeable pavement systems. Nevertheless, levelling of at least some parts of the site is required in 57% of all cases to allow for adequate flow by gravity.

The majority of all SUDS case study sites (83%) comprised only of one catchment. Only 13% and 5% of all sites had 2 and more than 2 sub-catchments, respectively. This finding indirectly supports the statement that many sites were flat (see above), which is beneficial for permeable pavement systems.

Only one site (1% of all sites) was seriously contaminated. It follows that permeable pavement systems used as infiltration devices are suitable for Greater Manchester. The soil infiltration rates were predominantly of medium magnitude (96%). Only 3% of the sites had low rates. Even fewer sites (1%) had high infiltration rates. The groundwater level was usually always relatively high, which is not a concern for permeable pavement systems.

4.3. Strengths and weaknesses of the site assessment

The traditional and new approach of estimating variables used for assessing SUDS retrofitting was based on a rapid site assessment adapted from Scholz (2006) and Scholz et al. (2006). The strengths of this site screening tool include quick, simple, inexpensive, user-friendly and easy-to-understand assessment of site data and physical site features, comprehensive dataset of the key variables hosted within a widely available non-expert data base such as Microsoft Excel; and acceptability of site does not discriminate against current site use. However, the following weaknesses of the methodology may apply: too simplified approach leaving wide room for interpretation and personal bias, and the assessment is not dynamic by nature, ignoring various possible future scenarios. These two negative points apply, however, also to the traditional approach proposed by CIRIA (2004).

4.4. Discussion of the ecosystem service variable assessment for Greater Manchester

This study combining ecosystem services assessments for sustainable drainage techniques with an expert system applied for a large database of real case studies is unique. Danso-Amoako et al. (2012) assessed large sustainable flood retention basins located within the wider Greater Manchester area previously. However, they only focused on a sub-set of the ecosystem services variables (Scholz and Yang, 2010) proposed in Table 3.1. Moreover, Gill et al. (2007) and White and Alarcon (2009) discussed green infrastructure in the context of climate change and planning policies associated with sustainable drainage in Greater Manchester, respectively, but were not concerned with the influence of ecosystem services variables on decision-making.

While Tables 3.1 and 3.2 outline the universal application of the ecosystem services variables, this section discusses the specific application of these variables for an example case study. A brief explanation regarding each new ecosystem service variable suitable for permeable pavement retrofitting with particular reference to selected sites in Greater Manchester is given below (see also Table 3.1 for generic descriptions).

Habitats for species (HS): A public park with a highly permeable surface coverage of diverse vegetation and structure-rich semi-natural watercourses will provide a great area for wildlife benefits, thus scoring highly. This habitat is unfortunately rare in Greater Manchester.

Maintenance of genetic diversity (MGD): The interconnectivity between sites providing habitats for a wide variety of ecosystems is often responsible for a relatively large number of species. The interconnectivity between and the quality of green spaces within Greater Manchester is relatively poor.

Local climate and air quality regulation (LCAR): Factors likely to reduce temperature and improve air quality in urban areas such as the density of tree coverage and the presence of surface water were assessed. A site, which is entirely covered by dense trees and contains surface water such as a pond will receive a relatively high ecosystem service potential value for this variable. The density of trees as well as the presence of water bodies is rather low in the example case study area.

Carbon sequestration and storage (CSS): This assessment was predominantly based on the density of tree coverage. Mature woodlands are rare within the study area.

Moderation of extreme events (MEE): The ability of a potential SUDS site to manage extreme events such as flooding, drought and fire was assessed. Sites that can mitigate runoff and store water that can subsequently be used as a resource will score highly. Thus, sites where permeable pavements can be implemented will be associated with high bin numbers. There is a high potential for retrofitted SUDS in Greater Manchester to score high on MEE.

Storm runoff treatment (SRT): The evaluation of this variable is based on the ability of a potential SUDS site to break down pollutants from surface runoff by physical, chemical and/or biodegradation processes. Some trees have a high potential to degrade pollutants. Thus the corresponding ecosystem service potential will be relatively high. There is an extraordinary potential for retrofitted SUDS in the study area to score relatively high on SRT.

Erosion prevention and maintenance of soil fertility (EPMSF): The potential of a SUDS site to protect its underlying soil from the harmful pollutants associated with surface runoff was evaluated. A site that is covered by dense and mature trees will have a high ecosystem service potential associated with this variable. There is a good opportunity for erosion prevention by a combination of permeable pavements and trees in Greater Manchester.

Pollination (P): The assessment was based on the likely presence of animals capable of encouraging and/or conducting pollination such as bees and butterflies. Sites that score high for this variable are associated with semi-natural green spaces such as parks, small woods and fields, which act as a habitat to such animals. P usually scores low in Greater Manchester and most other cities.

Biological control (BC): The assessment was based on the potential presence of predatory animals capable of regulating pests and diseases in the surrounding area. Sites that score high for this variable are associated with large parks and fields. The picture is rather mixed within the study area.

Food (F): The assessment was based on the potential of trees to provide food. The size of a site as well as its soil and associated contamination are important indirect evaluation parameter. A cultural change in the study area and a deepening of the current recession would be required to realize the potential of transforming parts of the potential SUDS sites into orchards.

Raw materials (RM): This evaluation considered the potential of a site to provide a range of raw materials such as wood. The active harvesting of RM is underutilized within most parts of the study area due to a lack of local policies promoting the multi-purpose use of green spaces. Moreover, most trees that could provide wood are of ornamental value and protected by law.

Fresh water (FW): The quantity and quality of surface runoff that a site is expected to receive was assessed. There is a great potential for FW to score high in terms of quantity across the study area. However, the water quality will be a function of the permeable pavement design and the presence of mature and dense vegetation such as trees.

Medicinal resources (MR): Some trees covering a potential SUDS site may have medicinal benefits for people and animals. This variable is unlikely to be relevant for the UK in the medium-term future.

Recreation, and mental and physical health (RMPH): The probable ability of a site to provide an area where people can interact with others through a wide range of activities including sport was considered. Large areas with cafes and space to play sports will score highest for this variable. There is an underutilized potential for RMPH in Greater Manchester, mainly due to cultural reasons.

Tourism and area value (TAV): This assessment was based on whether or not the attributes of a site are substantially attractive enough for people to come and visit the area from nearby neighbourhoods. A park, which is considered spectacular to Greater Manchester, may attract a relatively high number of local visitors, whereas a site such as the Manchester City Stadium will attract visitors from around the world. An attractive site is likely to result in higher house and land prices. There is a considerably underutilized potential for TAV to score high in Greater Manchester, mainly due to the presence of a few large parks suffering from under-investment.

Aesthetic and educational appreciation and inspiration for culture, art and design (AEAICAD): This evaluation is founded on the magnitude of a potential SUDS site in terms of its appeal to a high number of people of diverse backgrounds by creating areas where individuals can come and reflect, and find inspiration for a range of things. There is a considerably underutilized potential for AEAICAD to score high in Greater Manchester, mainly due to public under-investment.

Spiritual Experience and sense of place (SESP): A potential SUDS site's ability to encourage people to feel connected to the area and their associated community, giving them a strong sense of belonging, was evaluated. Considering the high multi-cultural diversity in Greater Manchester, there is a potential for SESP to score high in some areas.

4.5. Strengths of the new ecosystem services assessment approach

The new ecosystem service variables adapted for combined permeable pavement and tree systems are partly based on the previously published categories by TEEB (2011). The strengths of the new approach, particularly in comparison to the community and environment methodology adopted by Ellis et al. (2003) and CIRIA (2004), include a novel, innovative and generic approach based truly on universal ecosystem service variables and not on ecological engineering understanding. Furthermore, each bin in Table 2 is clearly defined thus leading to a quick and numerical (rather than a qualitative) assessment. An inexpensive, user-friendly and easy-to-understand evaluation is enabled. A comprehensive dataset of the key variables characterising a site hosted within a widely available non-expert data base is available. Finally, the overall ecosystem service potential of a site is expressed through an individual value.

Moore and Hunt (2012) proposed an alternative system based on the following ecosystem service variables for existing (not proposed as with the new approach) constructed wetlands and ponds used as SUDS: hydraulic, water quality, greenhouse gas regulation, air quality, climate, food, raw material, recreation, education, aesthetic and biodiversity. In comparison, the ecosystem service variables selected in this paper go beyond those proposed by Moore and Hunt (2012) who did not specifically consider HC (although referred to under biodiversity), MEE (although partly addressed under hydraulic), EPMSF, P, BC, FW, MR, TAV, AEAICAD (however, education is an independent variable) and SESP.

4.6. Limitations of the new ecosystem services assessment approach

Spatial assessments of landscape functions including urban ecosystem services by experts are an attractive challenge (Willemen et al., 2008). There are some potential weaknesses of the ecosystem services assessment approach. Subjectivity and aggregation are generic limitations of an expert-based system, which can be addressed by involving expert groups and determination of uncertainty values for all estimations (Munoz-Pedreros, 2004; Scholz and Yang, 2010; Danso-Amoako et al., 2012). Furthermore, some ecosystem service variables are not always applicable in the UK, because the proposed system has been designed to be universal and generic. There is also a strong perceived (falsely; see below) bias towards natural sites and ‘soft’ SUDS in contrast to urban sites and ‘hard’ SUDS such as traditional permeable pavements. Finally, there is a possibility of multi-collinearity among variables (McMinn et al., 2010).

Some of the above limitations such as subjectivity are also inherent in the traditional assessment approach (CIRIA, 2004, 2007). However, multicollinearity might be a more relevant problem with the proposed ecosystem services approach due to the use of more variables. Multicollinearity is a statistical phenomenon in which at least two predictor variables in a multiple regression model correlate highly with each other. Multicollinearity does not reduce the predictive power of a regression model. However, the model may not give correct results regarding any individual predictor or indicate which predictors are redundant. Considering that any tests for multicollinearity are case study-dependant, the inevitable bias associated with a case study does not allow for objective testing unless the number of case studies is very high and there is an adequate geographical spread to reduce bias. Nevertheless, a principal component analysis was carried out to identify redundant variables in order to reduce the risk of multicollinearity

(McMinn et al., 2010). However, all ecosystem services variables (Table 3.1) were considered to be necessary for the proposed expert system.

4.7. Comparison of assessment methods

Gill et al. (2007), McMinn et al. (2010) and Lundy and Wade (2011) recognise the need for a holistic assessment of green infrastructure including urban watercourses in the UK. Moreover, Lundy and Wade (2011) propose the integration of all relevant sciences to sustain ecosystem services. Assessment methods have evolved from previously representing only the views of a few stakeholder groups such as planners and civil engineers to as many views as voiced nowadays. The transition from the traditional (particularly CIRIA (2004)) to the proposed novel ecosystem services assessment approach for SUDS is a good example.

This section compares the assessment approaches discussed above with each other. The data obtained for the suitability of sites for the retrofitting of SUDS differs greatly depending on the approach used to carry out the assessment. All visited sites were considered suitable for the retrofitting of SUDS when the traditional assessment based on 'community and environment' (CIRIA, 2004) variables were carried out (Table 4.1 & 4.3). This differs greatly from the assessment performed using the new ecosystem services variables, where nearly half the sites visited are valued as having a relatively low ecosystem services potential, making them of limited use for retrofitting of most SUDS techniques. This finding can be used to prioritise sites for SUDS retrofitting.

This can be explained by the fact that most ecosystem service variables do relate well to the natural environment such as biologically diverse parks (41%) and not the built environment like impermeable car parks (33%). This relationship reduces the number of sites suitable for retrofitting of SUDS, as car parks only perform well with respect to three ecosystem service variables (MEE, SRT and FW; Table 3.2). The presence of public parks did not pull up the overall suitability of retrofitting sites, because they were usually small in size (30% of sites were <25,000 m^2), low in tree coverage (7%) and the presence of surface water (no streams, river (11%), canal (21%) and standing water (8%)) of the associated catchment was limited.

Table 4.1 gives the results of the assessment for the three approaches for all the 100 sites in Greater Manchester which followed similar methodological principles. It also shows a comparison of the three assessment approaches in terms of relative scores for all sites, indicating the evaluation differences between methods. However, the main difference lies in the selection of variables as outlined in sections 3.2.5, 3.2.6 and 3.2.7. The relative proportions for each SUDS technique have been expressed in percentage points for each column to allow for a direct comparison between approaches and preferences for the example case study area.

It could be observed from Table 4.1 that the assessed values for the traditional 'community and environment' approach were most times, consistently, higher than those of 'ecosystem service' approach. It could indicate that the traditional method (community and environment) approach supports the selection of most techniques which can be seen as too generous, time wasting and will require further effort to narrow the choice down. It also implies that most techniques could be chosen whether very relevant or not under traditional method. The ecosystem service variable approach seemed to be more thorough in selecting the most appropriate techniques either because it has more detailed assessment parameters or it identifies more appropriately the retrofitting problems to be addressed using the SUDS techniques. Furthermore, the combined approach (Table 4.1) seemed to have combined both the 'community and environmental' and 'ecosystem service' approaches very well since its assessed values were higher than those of 'ecosystem service' approach but lower than those of 'community and environment' approach considering that only the four main categories of ecosystem services were used for the 'combined' approach (as explained in section 3.2.7).

Table 4.2 shows a comparison of all assessment approaches in terms of the proposed SUDS options (including combined permeable pavement and tree system) for Greater Manchester. It outlined the number of times that each of the SUDS techniques were chosen as first, second and third preferences for all the three approaches. The preferences indicated in Table 4.2 were determined in a two-step process. Initially, the total scores for the SUDS technique assessed for every site were calculated for the three approaches. Considering that the maximum possible scores for each approach are different, a direct comparison of the SUDS technique popularity between the approaches is not meaningful. Therefore, the relative proportions for the SUDS technique have been expressed in percentage points in Table 4.2 to allow for a direct comparison between approaches and preferences. Note that there were many occasions where more than one SUDS technique had the same order of preference. It follows that the columns in Table 4 do not add up to 100.

Table 4.1. Comparison of the three assessment approaches (CE, Community and environment; ES, Ecosystem services; and C, Combined) for selecting SUDS techniques in terms of relative scores for all the 100 sites (expressed in percentage).

Site No	Permeable Pavement			Filter Strips			Swales			Green Roof			Pond			Constructed wetland			Infiltration Trench			Soakaway			Infiltration Basin			Belowground Storage			Water Playground		
	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C
1	56	35	44	60	39	51	56	32	42	0	0	0	68	62	65	0	0	0	60	28	43	68	28	46	44	29	38	60	27	40	56	32	44
2	68	32	48	0	0	0	44	32	36	0	0	0	0	0	0	0	0	0	0	0	0	68	25	44	0	0	0	68	27	46	0	0	0
3	60	32	45	52	31	43	56	33	45	0	0	0	60	69	58	0	0	0	68	29	46	64	29	44	48	29	38	52	27	34	56	24	36
4	76	32	48	0	0	0	56	32	44	0	0	0	0	0	0	0	0	0	44	25	39	68	25	44	0	0	0	68	27	46	0	0	0
5	68	29	15	64	39	53	56	32	44	0	0	0	0	0	0	0	0	0	60	28	46	68	25	44	0	0	0	56	27	37	64	32	47
6	68	0	0	68	31	48	52	32	39	0	0	0	0	0	0	0	0	0	64	28	46	68	29	46	0	0	0	68	27	46	0	0	0
7	0	0	0	52	39	48	56	32	42	0	0	0	68	64	63	0	0	0	68	26	47	68	28	46	0	0	0	60	27	40	64	32	47
8	76	32	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	26	42	68	26	45	0	0	0	68	26	45	0	0	0
9	0	0	0	56	34	48	48	32	42	0	0	0	76	74	72	0	0	0	64	29	44	68	29	46	40	28	35	0	0	0	60	28	42
10	0	0	0	64	40	51	40	32	36	0	0	0	88	62	71	0	0	0	60	28	46	68	28	46	40	28	35	0	0	0	68	32	50
11	0	0	0	56	29	41	40	32	36	0	0	0	68	61	62	0	0	0	68	25	44	68	25	44	40	28	35	56	27	37	64	26	43
12	0	0	0	76	34	50	60	32	44	0	0	0	96	68	79	100	62	68	36	25	33	68	25	44	52	28	35	68	27	46	44	27	35
13	0	0	0	60	29	44	40	32	36	0	0	0	68	61	62	0	0	0	60	25	42	68	25	44	0	0	0	0	0	0	56	26	38
14	68	29	47	68	39	53	52	32	42	0	0	0	92	61	71	100	62	68	64	25	44	68	25	44	0	0	0	68	27	46	68	32	53
15	56	32	45	56	33	44	0	0	0	0	0	0	0	0	0	0	0	0	64	25	42	64	24	41	0	0	0	56	26	37	0	0	0
16	68	32	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	26	37	68	26	45	0	0	0	68	26	45	0	0	0
17	56	32	45	56	29	44	0	0	0	0	0	0	0	0	0	0	0	0	64	25	42	64	24	41	0	0	0	52	26	34	0	0	0
18	0	0	0	72	36	52	0	0	0	0	0	0	92	66	76	0	0	0	60	29	47	68	29	15	0	0	0	0	0	0	40	75	63
19	64	29	44	48	35	43	48	31	40	0	0	0	68	66	67	68	74	43	68	28	46	68	28	46	48	33	37	56	27	37	52	31	38
20	0	0	0	56	35	46	44	32	36	0	0	0	92	68	76	0	0	0	60	25	44	68	28	46	0	0	0	0	0	0	0	0	0
21	60	32	48	56	35	46	0	0	0	0	0	0	0	0	0	0	0	0	64	25	42	64	25	42	0	0	0	56	26	37	0	0	0
22	0	0	0	68	42	55	44	32	39	0	0	0	96	79	85	100	73	73	64	28	46	68	28	46	44	28	38	0	0	0	60	27	44
24	60	31	16	68	39	53	48	31	39	0	0	0	92	69	77	68	69	40	60	27	45	68	25	44	48	33	37	0	0	0	56	29	43

Site No	Permeable Pavement			Filter Strips			Swales			Green Roof			Pond			Constructed wetland			Infiltration Trench			Soakaway			Infiltration Basin			Belowground Storage			Water Playground		
	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C
25	68	32	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	25	36	68	25	44	0	0	0	68	26	45	0	0	0
26	0	0	0	56	41	49	44	31	35	0	0	0	80	74	69	0	0	0	52	27	40	68	27	45	44	27	37	68	26	45	44	27	35
27	56	33	48	68	36	51	60	27	40	0	0	0	64	56	56	0	0	0	48	27	34	68	25	44	36	31	33	0	0	0	64	28	45
28	68	32	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	64	27	45	68	27	45	0	0	0	68	28	46	0	0	0
29	56	32	39	52	35	46	48	33	38	0	0	0	80	62	68	68	75	43	64	28	43	64	28	43	52	38	45	56	26	37	64	29	45
30	64	32	45	68	36	52	52	25	33	0	0	0	92	68	76	0	0	0	60	27	45	68	27	45	36	27	31	68	27	46	0	0	0
31	48	32	39	64	31	48	52	28	36	0	0	0	80	64	70	92	59	62	56	25	44	52	24	44	36	29	32	52	27	46	76	28	56
32	48	31	39	68	36	52	52	26	33	0	0	0	92	49	65	0	0	0	64	27	45	68	27	45	36	27	31	0	0	0	0	0	0
33	64	32	45	60	35	47	52	25	33	0	0	0	0	0	0	0	0	0	64	27	43	68	25	13	0	0	0	64	26	42	44	32	35
34	60	32	45	0	0	0	0	0	0	0	0	0	64	61	57	68	73	62	56	27	45	68	28	46	0	0	0	0	0	0	76	32	55
35	60	32	45	60	29	47	44	32	36	0	0	0	0	0	0	0	0	0	68	27	46	64	26	42	36	26	31	68	26	45	0	0	0
36	52	31	47	60	42	56	44	32	36	0	0	0	84	74	72	0	0	0	52	27	34	64	27	14	48	28	35	0	0	0	0	0	0
37	60	32	45	56	35	47	36	25	27	0	0	0	0	0	0	0	0	0	68	27	46	68	25	44	36	27	31	60	26	39	0	0	0
38	68	31	47	56	29	41	44	28	35	0	0	0	0	0	0	0	0	0	48	27	40	68	25	44	0	0	0	68	27	46	0	0	0
39	64	33	45	0	0	0	44	29	35	0	0	0	0	0	0	0	0	0	48	27	40	60	26	39	0	0	0	68	27	46	0	0	0
40	68	32	48	0	0	0	56	26	39	0	0	0	0	0	0	0	0	0	64	27	45	68	27	45	0	0	0	68	28	46	0	0	0
41	56	33	40	56	42	50	0	0	0	0	0	0	0	0	0	0	0	0	60	27	42	68	27	45	0	0	0	52	27	46	0	0	0
42	68	29	47	0	0	0	52	26	36	0	0	0	0	0	0	0	0	0	64	27	45	68	27	45	0	0	0	68	29	47	0	0	0
43	60	32	45	48	36	44	44	26	34	0	0	0	0	0	0	0	0	0	68	27	46	64	25	42	0	0	0	60	26	39	0	0	0
44	56	31	39	72	42	55	48	32	39	0	0	0	92	71	76	0	0	0	52	28	46	68	28	46	44	28	38	0	0	0	52	27	41
45	60	33	48	44	40	45	36	28	32	0	0	0	68	71	66	68	71	71	52	27	42	68	26	45	44	29	35	68	27	46	64	32	47
46	72	33	51	0	0	0	44	26	31	0	0	0	0	0	0	0	0	0	68	27	45	68	27	45	0	0	0	68	28	46	0	0	0
47	64	32	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	48	27	34	68	27	46	0	0	0	68	27	46	0	0	0
48	68	36	51	0	0	0	0	0	0	0	0	0	84	68	76	0	0	0	64	27	45	68	27	45	0	0	0	0	0	0	0	0	0
49	56	33	40	68	35	52	0	0	0	0	0	0	64	56	58	0	0	0	64	29	46	68	29	46	36	31	33	0	0	0	64	32	47
50	72	32	51	0	0	0	44	25	30	0	0	0	0	0	0	0	0	0	68	27	45	68	27	45	0	0	0	68	28	46	0	0	0

Site No	Permeable Pavement			Filter Strips			Swales			Green Roof			Pond			Constructed wetland			Infiltration Trench			Soakaway			Infiltration Basin			Belowground Storage			Water Playground		
	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C
51	72	33	51	68	42	55	0	0	0	0	0	0	0	0	0	0	0	0	52	27	37	68	27	45	0	0	0	0	0	0	0	0	0
52	72	33	34	0	0	0	44	26	31	0	0	0	0	0	0	0	0	0	68	27	45	68	27	45	0	0	0	68	28	46	0	0	0
53	0	0	0	64	26	43	44	25	33	0	0	0	0	0	0	0	0	0	64	27	45	64	26	42	0	0	0	0	0	0	40	27	33
54	56	31	39	68	31	46	44	32	33	0	0	0	64	61	57	96	75	75	64	29	46	68	28	46	0	0	0	0	0	0	64	32	50
55	64	33	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	68	26	45	68	26	45	0	0	0	64	26	42	0	0	0
56	68	32	48	68	31	48	52	26	36	0	0	0	88	68	79	0	0	0	64	27	45	68	27	45	0	0	0	68	28	46	0	0	0
57	0	0	0	60	31	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	64	27	42	0	0	0	60	26	39	0	0	0
58	56	33	40	52	41	46	40	31	32	0	0	0	76	74	69	0	0	0	52	27	37	68	27	45	40	27	34	68	27	46	0	0	0
59	68	32	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	56	26	39	56	25	40	36	27	31	68	27	46	0	0	0
60	68	32	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	28	46	68	27	45	0	0	0	68	27	46	0	0	0
61	56	33	40	68	34	50	44	25	31	0	0	0	0	0	0	0	0	0	68	28	46	68	28	46	0	0	0	52	27	34	56	27	23
62	68	33	31	0	0	0	44	26	33	0	0	0	0	0	0	0	0	0	68	27	45	68	27	45	0	0	0	68	28	46	0	0	0
63	60	33	26	68	42	55	0	0	0	0	0	0	60	74	64	0	0	0	56	28	40	64	27	42	36	29	32	0	0	0	48	27	17
64	0	0	0	68	36	50	48	25	33	0	0	0	92	56	72	0	0	0	64	35	50	68	33	49	36	32	33	0	0	0	64	29	49
65	0	0	0	68	42	55	0	0	0	0	0	0	64	60	60	0	0	0	68	34	49	68	34	49	44	32	36	0	0	0	64	31	46
66	56	33	40	52	27	37	0	0	0	0	0	0	72	68	68	0	0	0	68	27	45	68	27	45	0	0	0	68	27	46	0	0	0
67	64	32	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	48	27	42	64	27	14	52	26	39	64	28	43	0	0	0
68	64	33	45	64	42	53	0	0	0	0	0	0	96	68	79	0	0	0	60	28	43	68	27	45	0	0	0	0	0	0	0	0	0
69	64	32	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	48	27	42	64	27	42	52	26	39	64	28	43	0	0	0
70	60	28	43	72	31	48	56	33	42	0	0	0	88	66	76	0	0	0	64	29	46	68	29	46	44	29	38	0	0	0	64	24	42
71	64	32	45	68	27	47	0	0	0	0	0	0	0	0	0	0	0	0	60	26	42	68	25	44	52	26	39	56	26	37	0	0	0
72	0	0	0	64	42	55	48	24	36	0	0	0	88	68	76	0	0	0	64	28	46	68	27	45	0	0	0	0	0	0	60	28	42
73	0	0	0	52	31	40	56	33	42	0	0	0	72	67	65	64	75	66	56	29	41	64	29	44	36	29	32	0	0	0	52	24	39
74	0	0	0	60	31	48	44	33	37	0	0	0	84	67	74	0	0	0	68	29	46	68	29	46	48	29	38	0	0	0	64	24	42
75	0	0	0	60	28	42	0	0	0	0	0	0	0	0	0	0	0	0	56	27	42	64	27	42	52	29	41	0	0	0	56	28	39
76	60	28	43	72	31	48	56	34	45	0	0	0	96	68	80	96	68	69	52	31	45	68	31	47	52	31	43	0	0	0	64	28	16

Site No	Permeable Pavement			Filter Strips			Swales			Green Roof			Pond			Constructed wetland			Infiltration Trench			Soakaway			Infiltration Basin			Belowground Storage			Water Playground		
	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C	CE	EC	C
77	68	32	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	26	45	60	26	39	0	26	14	68	28	46	0	0	0
78	68	32	48	0	0	0	40	32	33	0	0	0	0	0	0	0	0	0	0	0	0	68	27	45	0	0	0	68	27	46	0	0	0
79	56	32	39	68	27	46	0	0	0	0	0	0	0	0	0	0	0	0	60	29	44	68	28	46	0	0	0	56	27	37	0	0	0
80	68	32	48	56	28	45	0	0	0	0	0	0	0	0	0	0	0	0	64	27	45	68	27	45	0	0	0	68	27	46	0	0	0
81	0	0	0	60	42	50	0	0	0	0	0	0	0	0	0	0	0	0	60	27	42	64	27	42	0	26	14	0	0	0	0	0	0
82	0	0	0	0	0	0	0	0	0	0	0	0	80	68	71	100	75	75	0	0	0	68	29	46	0	0	0	68	27	46	0	0	0
83	68	32	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	27	42	68	27	45	52	26	39	68	28	46	0	0	0
84	68	32	48	0	0	0	40	32	33	0	0	0	0	0	0	0	0	0	64	27	42	68	27	45	0	0	0	68	28	46	0	0	0
85	0	0	0	68	42	55	0	0	0	0	0	0	0	0	0	0	0	0	68	27	45	0	0	0	0	0	0	60	27	40	0	0	0
86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	29	46	68	29	46	52	26	39	68	27	46	0	0	0
87	60	32	45	60	33	44	44	27	34	0	0	0	60	55	54	0	0	0	52	27	37	68	27	45	36	32	35	0	0	0	0	0	0
88	68	32	48	0	0	0	40	33	34	0	0	0	0	0	0	0	0	0	68	27	45	68	27	45	0	0	0	68	26	45	0	0	0
89	0	0	0	64	35	51	44	25	33	0	0	0	44	68	51	0	0	0	44	27	34	68	27	45	36	27	31	56	27	37	56	27	36
90	60	32	45	56	31	43	44	33	37	0	0	0	0	0	0	0	0	0	68	31	47	68	28	31	44	27	37	0	0	0	60	28	42
91	64	32	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	27	45	68	27	14	52	26	39	68	26	45	0	0	0
92	68	34	49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	68	27	45	68	27	45	0	0	0	68	27	46	0	0	0
93	64	34	46	56	29	39	0	0	0	0	0	0	0	0	0	0	0	0	52	28	46	64	27	42	0	0	0	64	29	44	0	0	0
94	56	34	40	60	27	40	40	33	34	0	0	0	76	68	68	0	0	0	68	27	31	68	29	46	0	0	0	68	27	46	0	0	0
95	68	34	49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	26	39	68	27	46	0	0	0
96	0	0	0	72	42	55	44	33	37	0	0	0	96	67	78	100	75	75	0	0	0	68	28	46	52	26	39	0	0	0	0	0	0
97	68	35	51	68	29	47	0	0	0	0	0	0	0	0	0	0	0	0	48	28	35	68	27	45	52	26	39	0	0	0	0	0	0
98	60	33	45	0	0	0	44	33	37	0	0	0	92	56	67	0	0	0	48	29	44	68	28	46	36	27	31	0	0	0	60	29	43
99	68	34	49	68	36	52	0	0	0	0	0	0	0	0	0	0	0	0	52	28	40	68	28	46	36	26	31	52	28	41	0	0	0
100	68	34	49	60	42	53	56	33	42	0	0	0	0	0	0	0	0	0	0	0	0	68	28	46	0	0	0	68	27	46	0	0	0

Table 4.2. Comparison of assessment approaches in terms of choice preferences for sustainable drainage system (SUDS) techniques for all selected sites in Greater Manchester.

SUDS Technique	Proportion (%) of sites at which SUDS techniques are given first, second or third order of preference for the **community and environment** approach			Proportion (%) of sites at which SUDS techniques are given first, second or third order of preference for the **ecosystem service** approach			Proportion (%) of sites at which SUDS techniques are given first, second or third order of preference for the **combined** approach		
	First	Second	Third	First	Second	Third	First	Second	Third
Permeable pavement	32	16	20	34	17	15	31	11	14
Filter strip	11	25	30	14	32	20	17	29	12
Swales	0	5	22	8	9	20	0	0	7
Green roof	0	2	15	0	0	7	0	0	1
Pond	31	9	18	36	9	7	40	5	1
Constructed wetland	8	6	15	11	3	7	5	6	1
Infiltration trench	19	26	30	2	11	39	7	17	30
Soakaway	51	34	10	1	11	31	4	20	41
Infiltration basin	0	6	18	1	1	19	0	3	3
Below-ground storage	29	19	12	1	25	13	7	28	10
Water playground	1	11	26	2	3	14	0	2	12
TOTAL	**182**	**159**	**216**	**110**	**121**	**192**	**111**	**121**	**132**
Occurrences where an option was in the Top 3 preferences	**557**			**423**			**364**		

Only the first, second and third highest preferences have been shown in Table 4.2, because the assessors associated relatively high confidence values with these selections. This procedure allows for the easy comparison between the three assessments methods applied to all selected sites in Greater Manchester (Fig. 3.1). Furthermore, a full rank-order correlation analysis was not considered to be carrying great weight, because uncertainties associated with less preferred SUDS options were considerably higher than those associated with the top three choices.

From Table 4.2, it could be observed that 'ecosystem service approach raised a higher preference for permeable pavements, filter strips, swales, pond, constructed wetlands, and water playgrounds; while the traditional 'community and environment' approach raised the preference for infiltration trench, soakaway and below-ground storage.

In general, the number of times that each technique was chosen for the first, second and third preferences were highest under the traditional 'community and environment' approach (Table 4.2). Although the 'combined' approach recorded the lowest choice of techniques for first, second and third preference (Table 4.2), it may appear to be more precise in assessment, but however, considering that the variables used for the 'combined' approach were not spread out (only 7), a better choice should be the 'ecosystem service' approach which had 17 variables that thoroughly covered all aspects of SUDS benefits including flood control, aesthetics, etc.

Table 4.3 shows a comparison of the inter-site variability (expressed by the standard deviation) for a given sustainable drainage technique for Greater Manchester, and helps to interpret the practice preferences distributions in Table 4.2. The new ecosystem services and the traditional assessment approaches have usually the lowest and highest inter-site variability, respectively. The relatively high variability for most variables such as ponds and constructed wetlands cannot be explained by factors relating to specific planning policies for Greater Manchester (White & Alarcon, 2009). Ponds are associated with the greatest inter-site variability, as indicated by standard deviation, for all three approaches because of their potentially relatively small size and great popularity (Scholz, 2004, 2010; Scholz et al., 2006), particularly with the traditional approach (Table 4.3).

From Table 4.3, it could be stated that the values awarded for soakaways in all sites were the most precise among other techniques for all approaches as indicated by the coefficient of variation.

The mean and standard deviation of each SUDS technique in 'ecosystem service' approach is generally lower compared to the corresponding mean and standard deviation values in 'community and environmental' approach. This indicates that the points awarded using the 'community and environment' approach appears to be more generous and not precise, and could be misleading. Standard deviation being higher in the 'community and environment' variable indicates that the points awarded for each technique differed more compared to using the 'ecosystem service' approach.

Table 4.3: Comparison of the inter-site variability for sustainable drainage techniques for Greater Manchester.

SUDS Technique	Mean and Standard deviations (based on relative percentage points awarded)								
	Community and environment approach			Ecosystem services approach			Combined approach		
	Mean	Standard Dev.	Coeff. of Variation	Mean	Standard Dev.	Coeff. of Variation	Mean	Standard Dev.	Coeff. of Variation
Permeable pavement	47.96	27.77	0.58	23.95	14.05	0.59	32.99	20.09	0.61
Filter strip	41.86	29.64	0.71	23.70	17.00	0.72	32.61	22.98	0.70
Swale	28.20	23.81	0.84	17.68	14.84	0.84	21.77	18.30	0.84
Green roof	0.00	0.00	-	0.00	0.00	-	0.00	0.00	-
Pond	35.92	40.52	1.13	29.88	33.14	1.11	31.32	34.90	1.11
Constructed wetland	12.00	30.28	2.52	9.98	24.81	2.49	8.98	22.69	2.53
Infiltration trench	50.07	17.06	0.34	25.48	7.27	0.29	40.04	11.71	0.29
Soakaway	65.49	9.81	0.15	26.54	4.24	0.16	42.21	9.34	0.22
Infiltration basin	19.88	22.33	1.12	13.46	14.34	1.07	16.63	18.02	1.08
Below-ground storage	42.59	30.63	0.72	18.04	12.84	0.71	28.84	20.74	0.72
Water playground	22.51	29.15	1.29	11.43	15.37	1.34	16.04	21.23	1.32

4.8. Permeable pavement with tree combination

This study also focused on permeable pavements and tree combinations because of: its role as a point source in erosion control, its high aesthetic value, and its versatility use in development/regeneration projects. Therefore, the permeable pavement option was also compared against the following alternative SUDS techniques in terms of preference for all case study sites: filter strip, swale, green roof, pond, constructed wetland, infiltration trench, soakaway, infiltration basin, belowground storage and water playground. Inter-site variability (Table 4.2) also indicate that the assessment values for permeable pavements and tree system using the ecosystem service approach were closer together than those of traditional 'community and environment' and combined approaches.

4.9. Trees suitable for urban areas

Table 4.4 shows an overview of identified trees and their suitability for urban permeable pavement sites in Greater Manchester and other cities with temperate and oceanic climates. The suitability has been determined based on expert judgement and a literature review. However, opinions on individual characteristics were sometimes diverse and controversial. Therefore further site studies will later be carried out based on the damage characteristics of most of these tree species on structures.

The most generically suitable trees were *Acer platanoides* (Norway Maple), *Acer pseudoplatanus* (Sycamore), *Alnus glutinosa* (Common Alder), *Betula pendula* (Silver Birch), *Cupressus* × *leylandii* (Leyland Cypress or Leylandii), *Robinia pseudoacacia* (Black Locust or False Acacia), *Platanus* × *acerifolia* (London Plane) *Quercus palustris* (Pin Oak) and *Tilia* × *europaea* (Common Lime). In contrast, the most generically unsuitable trees for streets and permeable pavements were *Aesculus hippocastanum* (Horse Chestnut), *Populus* spp. (Poplar), *Salix babylonica* (Weeping Willow), *Tilia* *platyphyllos* (Large-leafed Lime) and *Ulmus procera* (English Elm) as indicated in Table 4.5.

Table 4.5 shows the findings of a tree survey located within a strip of 10 m adjacent to areas where permeable pavements could be retrofitted in selected case study areas of Greater Manchester. From literatures, at least 66% of the trees determined are suitable for permeable pavements. The trees with the highest proportions are *Acer pseudoplatanus* (34%), *Tilia* × *europaea* (26%). *Betula pendula* (4%), *Alnus glutinosa* (1%) and *Cupressus* × *leylandii* (1%). In comparison, only about 4% of the identified trees are unsuitable for retrofitting of permeable pavements. The highest proportions were associated with *Populus* spp. (2%), *Aesculus hippocastanum* (1%) and *Salix babylonica* (1%). Approximately 30% of trees identified are likely to have a neutral impact on permeable pavement retrofitting.

Table 4.4 can be used to specify generically some permeable pavement design and construction details, and can also be applied for the example case study in combination with Table 4.5. For example, the minimum strip width for planting trees in order to protect tree roots and nearby building structures is specified in Table 4.4 (column 8). If practitioners follow the guidelines in Table 4.4, permeable pavements and trees are less likely to have a negative impact on each other.

However, Table 4.5 shows that *Acer pseudoplatanus* is only dominant (i.e. highest individual tree counts) on five sites. Furthermore, *Tilia* × *europaea* dominates just two sites.

Table 4.4: Overview of the potential suitability of identified trees for permeable pavement sites in Greater Manchester and other cities with temperate and oceanic climates.

Species	Common English name	Suitability for urban environment and particularly for permeable pavements	Soil type	Site characteristics	Features	Planted under wires?	Minimum strip width (m)	Mature crown spread (m) spread (m)	Tree height (m)	Reference[a]
Acer platanoides	Norway Maple	Suitable for sub-urban developments, recreation areas, small parks, and streets, roads and permeable pavements	Recommended for wet soils, clay soils, chalk soils and dry sandy soils; not recommended for industrial spoils	Strongly recommended for smoke and fume sites; recommended for seaside and exposed sites	Strongly recommended for flowers and leaves	No	2.0	12	12 to 25	3 to 5
Acer pseudopla-tanus	Sycamore	Suitable for urban fringe woodlands, large parks, and roads, streets and permeable pavements	Strongly recommended for industrial spoils; recommended for wet soils, clay soils and chalk soils; not recommended for dry sandy soils	Strongly recommended for seaside, exposed sites, smoke and fumes sites; not for ecologically sensitive habitats (non-native in the UK)	Nothing particular	No	1.5	9	16 to 35	3 to 5
Aesculus hippocasta-num	Horse Chestnut	Not recommended for roads, streets and permeable pavements	Recommended for wet soils, clay soils, chalk soils and dry sandy soils; not recommended for industrial spoils	Strongly recommended for smoke and fumes; recommended for seaside and exposed sites.	Recommended for flowers and fruits (unsuitable for paved areas)	No	2.0	11	16 to 35	3 to 5
Alnus glutinosa	Common Alder	Suitable for urban fringe woodlands, large parks, road sides and permeable pavements	Recommended for wet, clay and chalk soils; also recommended for industrial spoils; not recommended for dry sandy soils	Recommended for exposed sites; strongly recommended for smoky and fumy conditions	Not recommended for flowers and fruits	No	2.0	13	18 to 25	3 to 5
Betula pendula	Silver Birch	Suitable for parks, roadsides, streets and permeable pavements	Strongly recommended for dry sandy soils and industrial spoils; recommended for clay soils; not recommended for wet soils and chalk soils	Strongly recommended for exposed sites; recommended for seaside, smoke and fume sites, small spaces	Not recommended for bark	No	1.5	10	18 to 25	3 to 5
Carpinus betulus	European Hornbeam	Avenue, streets and permeable pavements on rare occasions	Strongly recommended for clay soils; recommended for wet, chalk and dry sandy soils; not recommended for industrial spoils	Recommended for exposed sides, and smoke and fumes; not recommended for seaside	Not recommended for flowers; leaves (autumn	No	1.5	5	10 to 20	2, 3 and 5

					colour)				
Crataegus monogyna	Common Hawthorn	Suitable for urban fringe woodlands, large parks and only sometimes for roadsides, streets and permeable pavements	Strongly recommended for industrial spoils; recommended for wet soils, clay soils and chalk soils; not recommended for dry sandy soils	Strongly recommended for seaside and exposed sites; recommended for smoke and fumes sites	Not recommended for flowers and fruits	No	1.5	8	12 to 15	2, 3 and 5
Cupressus × leylandii	Leyland Cypress (also Leylandii)	Suitable for urban fringe woodlands, large parks, roadside and permeable pavements	Strongly recommended for clay soils; recommended for wet soils, chalk soils, dry sandy soils and industrial spoils	Strongly recommended for seaside and exposed sites; recommended for smoke and fume sites	Strongly recommended for hedges and as screens	No	3.0	11	12 to 40	3 to 5
Robinia pseudo-acacia	Black Locust (also False Acacia)	Strongly recommended for roads, streets and permeable pavements	Strongly recommended for dry soils and industrial spoils; recommended for clay and chalk soils	Strongly recommended for smoke and fumes sites; recommended for seaside; not recommended for exposed sites	Nothing particular	No	1.5	8 to 25	12 to 52	3 to 5
Fagus sylvatica	Common Beech	Suitable for urban fringe woodlands, large parks and roadsides	Strongly recommended for chalk soils and dry sandy soils; not recommended for industrial spoils	Recommended for seaside; strongly recommended for exposed sites; unsuitable for smoke and fumes sites	Not recommended for leaves	No	1.8	12	15 to 49	3 to 5
Fraxinus excelsior	Common Ash	Suitable for urban fringe woodlands, large parks and road sides	Strongly recommended for chalk soils; recommended for clay soils; not recommended for wet soils	Strongly recommended for exposed sites, smoke and fumes; recommended for seaside	Nothing particular	No	1.8	9 to 15	15 to 46	3 and 4
Ilex spp.	Holly	Some streets and roads	Strongly recommended for clay, chalk, and dry sandy soils; recommended for wet soils	Strongly recommended for seaside, exposed sites, and smoke and fumes sites	Not recommended for fruits	No	1.5	2 to 9	8 to 15	3 and 5
Platanus × acerifolia	London Plane	Recommended for avenues, roads, streets and permeable pavements (tolerant of root compaction)	Strongly recommended for clay soils; recommended for wet soils, chalk soils, dry sandy soils and industrial spoils	Strongly recommended for seaside, smoke and fume sites; recommended for exposed sites	Not recommended for barks and leaves.	No	2.4	12	18 to 40	2 and 5
Populus spp.	Poplar	Not to be planted near buildings	Strongly recommended for wet and clay soils; recommended for chalk soils; not recommended for dry sandy soils	Recommended for seaside, exposed sites, smoke and fumes sites	Nothing particular	No	2.0	3 to 7	15 to 20	3 to 5
Prunus spp.	Cherry	Usually suitable for suburban developments recreation areas, small parks, roads, streets and permeable pavements	Strongly recommended for clay soils; recommended for chalk soils and dry sandy soils	Recommended for seaside, smoke and fumes; unsuitable for exposed sites	Recommended for flowers; not recommended for fruits	Usu-ally yes	1.5 to 2.5	2 to 7	6 to 8	3 to 5

Quercus palustris	Pin Oak	Recommended for avenues, roads, streets and permeable pavements	Strongly recommended for clay soils; recommended for wet soils and dry sandy soils	Recommended for smoke and fumes sites	Not recommended for leaves	No	2.0	6 to 14	15 to 25	1, 2 and 5
Quercus robur	Common Oak	Suitable for urban fringe woodlands, large parks and road sides	Strongly recommended for clay soils; recommended for wet soils and dry sandy soils; not recommended for chalk soils and industrial spoils	Recommended for seaside, and smoke and fumes	Not recommended for leaves	No	2.4	4 to 12	15 to 25	3 to 5
Quercus rubra	Red Oak	Suitable for suburban developments, recreation areas, small packs and some streets	Recommended for wet soils, clay soils, dry sandy soils and industrial spoils; not recommended for chalk soils	Strongly recommended for smoke and fumes sites; not recommended for seaside, exposed sites	Recommended for leaves	No	2.4	14	10 to 25	3 to 5
Salix babylonica	Weeping Willow	Usually not recommended for urban areas (destructive root system)	Recommended for wet soils	Recommended near watercourses	Not recommended for barks	No	10.0	10 to 12	20 to 25	3 to 5
Salix caprea	Goat Willow	Suitable for city centre developments, office blocks and formal gardens	Strongly recommended for clay soils and industrial spoils; recommended for dry sandy soils; not recommended for wet soils.	Recommended for seaside; not recommended for exposed sites	Not recommended for flowers	No	4.0	4 to 12	6 to 13	3 to 5
Tilia × europaea	Common Lime	Parks, avenues, streets and permeable pavements	Recommended for wet and clay soils; not recommended for industrial spoils	Recommended for seaside, exposed sites, and smoke and fumes sites	Not recommended for leaves	No	2.0	7 to 17	15 to 50	2, 4 and 5
Tilia platyphyllos	Large-leafed Lime	Not recommended for roads, streets and permeable pavements	Strongly recommended for clay soils; recommended for wet soils, chalk soils and dry sandy soils; not recommended for industrial spoils	Strongly recommended for exposed sites, and smoke and fumes sites; recommended for seaside	Nothing particular	No	2.0	8 to 18	18 to 40	3 to 5
Ulmus procera	English Elm	Suitable for roads and streets but not recommended (vulnerable to the Dutch Elm disease)	Prefers nutrient-rich soils; recommended for wet soils, clay soils and chalky soils	Usually found in rural farmland; recommended for seaside, exposed sites, smoke and fume sites	Not recommended for leaves	No	1.8	5 to 11	16 to 30	3 to 5

[a]Reference examples: 1, Elmendorf et al. (2005); 2, Essex County Council (2012); 3, Hibberd (1989); 4, Woodland Trust (2012); 5, Seattle Department of Transportation (2012)

Table 4.5: Number of trees (at least 10 cm in diameter at a height of 1.5 m) within a strip of 10 m adjacent to areas where permeable pavements could be retrofitted in selected case study areas of Greater Manchester.

Site	*Acer platanoides*	*Acer pseudoplatanus*	*Aesculus hippocastanum*	*Alnus glutinosa*	*Betula pendula*	*Carpinus betulus*	*Crataegus monogyna*	*Cupressus × leylandii*	*Robinia pseudoacacia*	*Fagus sylvatica*	*Fraxinus excelsior*	*Ilex* spp.	*Platanus × acerifolia*	*Populus* spp.	*Prunus* spp.	*Quercus palustris*	*Quercus robur*	*Quercus rubra*	*Salix babylonica*	*Salix caprea*	*Tilia × europaea*	*Tilia platyphyllos*	*Ulmus procera*	Other tree species	Total number	Proportions (%)
1	0	13	2	0	3	1	5	0	3	6	10	1	0	0	7	0	2	0	3	0	6	0	0	10	72	5
7	0	7	2	0	0	0	0	0	0	3	18	0	0	0	0	0	0	0	1	0	3	0	0	1	35	2
9	0	87	0	0	4	0	0	0	0	13	19	17	0	0	12	1	0	0	6	0	150	3	0	2	314	21
12	0	14	5	0	0	0	2	3	0	10	1	0	0	0	0	0	0	0	0	0	4	0	0	2	41	3
18	0	5	0	0	2	0	0	2	0	4	2	4	0	0	8	0	1	1	0	1	9	0	0	1	40	2
19	1	51	2	0	0	1	0	2	0	4	5	2	0	0	0	0	3	0	0	0	46	0	1	0	118	8
20	0	6	0	0	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0
22	0	75	0	0	0	0	0	0	0	3	14	0	0	0	3	0	0	0	0	0	0	0	0	0	95	6
24	0	45	0	0	1	0	1	0	0	0	0	0	0	0	3	0	0	0	0	0	49	0	0	2	101	6
29	0	44	0	0	3	0	19	0	0	20	20	0	0	0	2	0	0	0	0	0	50	0	0	7	165	11
30	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	7	0	0	1	11	1
36	0	32	0	0	0	0	0	0	0	2	1	0	0	0	1	0	0	0	0	0	14	0	0	0	50	3
43	0	3	0	0	0	0	0	0	0	1	0	0	0	0	4	0	0	0	0	0	14	0	0	0	22	1

44	0	21	1	6	20	1	3	1	0	21	21	10	0	0	28	0	9	0	2	0	11	0	0	11	166	11
64	0	38	1	0	0	0	0	0	0	0	0	0	1	29	10	4	0	0	0	0	5	0	0	2	90	6
70	0	19	0	2	22	0	0	0	0	0	0	0	0	0	15	1	0	0	0	0	9	0	0	5	73	5
71	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
74	0	24	0	1	1	0	0	0	0	0	1	0	0	0	11	0	0	0	4	0	0	0	0	1	43	3
86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
87	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	2	0	0	0	11	1
89	0	5	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	11	1
98	0	10	0	0	0	0	1	0	0	0	2	0	0	2	6	0	0	0	0	0	6	0	0	0	27	2
Total number	1	500	13	9	62	3	31	8	3	88	125	34	1	31	110	6	16	1	17	1	387	3	1	46	1497	100
Proportion (%)	0	34	1	1	4	0	2	1	0	6	9	2	0	2	7	0	1	0	1	0	26	0	0	3	100	

Tree diversity was lacking in Greater Manchester, because two species accounted for 60% of all trees specified (Table 4.5). However, it is not unusual to have large numbers of popular species planted in cities. For example, in Hong Kong, the top ten dominant species are 56% of the population. *Aleurites moluccana* constitutes 13% of the tree population (Jim, 1996). In Chicago, the ten most common species account for 46% of the urban trees (Nowak et al., 2010). In Nordic cities, 30–90% of all trees planted belong to a single species (Sæbø et al., 2003). In other European cities, only three to five genera usually accounted for 50–70% of all street trees planted (Pauleit et al., 2002).

4.10. Chapter Summary

Analysis of the feasibility and site assessments for the retrofitting of SUDS in 100 sites in Greater Manchester was carried out and discussed. The strengths and weaknesses of the site assessments were also discussed. The results of the ecosystem service assessments were also discussed highlighting its strengths and weaknesses, including its limitations.

In comparing the assessment methods (approaches), it was observed that the assessed values for the traditional 'community and environment' approach were most times, consistently, higher than those of 'ecosystem service' approach, indicating that the traditional method (community and environment) approach supports the selection of most techniques which can be seen as too generous, time wasting and will require further effort to narrow the choice down. It also implies that most techniques could be chosen whether very relevant or not under traditional method.

Ecosystem service approach gave a more focused assessment of the SUDS retrofitting options because it has the most variables (17) which thoroughly addresses all SUDS benefits and requirements

Comparison of the inter-site variability, which helped to interpret the practice preferences distributions revealed that the new ecosystem services and the traditional assessment approaches have usually the lowest and highest inter-site variability, respectively. This confirms the precision and consistency of the ecosystem service approach.

The number of times that each technique was chosen for the first, second and third preferences were highest under the traditional ‘community and environment’ approach. Although the ‘combined’ approach recorded the lowest choice of techniques for first, second and third preference, which may appear to be more precise in assessment, but however, considering that the variables used for the ‘combined’ approach were not spread out (only 7), the ‘combined’ approach may not have thoroughly reflected all the benefits of SUDS which may adequately influence its choice.

Tree availability on site was also noted, and based on literatures studies, at this stage, certain tree species were recommended.

CHAPTER 5

INTRODUCTION OF WEIGHTING SYSTEMS FOR DIFFERENT PROFESSIONS: RESULTS AND DISCUSSION

5.1. Overview

This chapter discusses the introduction of weighting systems to reflect the perspectives of different professions likely to be involved in the decision process of SUDS retrofitting.

Some of the results and discussions in this chapter, including figures and tables, already formed part of the paper published in paper no. 2 on page viii.

5.2. The Learning process of estimations using civil engineering Students

Results of the questionnaire administered to the students of Social Science, Ecology and Civil Engineering were used to assess the learning process of estimation through three-stage progressive estimations of variables. However, Civil Engineering students' results were used to analyse how repeated trials in estimation may affect improvements or learning, and reduce variability (Fig. 5.1).

An estimation tool has to be relatively simple to learn and apply (Bolger and Wright, 1994), and should be based more on intuition than on expert understanding to limit the variability associated with estimations for the same variable by different assessors with potentially diverse backgrounds. Table 5.1 shows the findings of the questionnaire analysis, while Fig. 5.1 gives a clear understanding of the progression achieved by the civil engineering students from one stage to another.

Considering that the concept of "estimation" was new to the students, and they were neither briefed nor trained in advance of the questionnaire, someone might expect considerable progressive learning from stage to stage. However, learning or repeated assessments caused a clear improvement only in land size estimation between all stages (Fig. 5.1, Table 5.1). Fig. 5.1 shows that the estimations in *habitat for species* were consistently very similar and linear among the three stages. There were just a slight improvement in *aesthetics* and *land cost*. Moreover, there was an expectation to identify a clear reduction in variability (indicated by the standard deviation) as learning progressed. Nevertheless, this was not clearly the case (Fig. 5.1, Table 5.1). Reason for this could be that, three trials taken at once were not sufficient enough to make any significant reduction in variability. However, experience over a period of time may reduce variability and increase certainty in estimations. Stage 3 results were generally and consistently more linearly spread than those of stages 1 and 2. This could be because, as the students had all the site pictures at once on one page, they could make a better comparison among the pictures, but improvement in estimations and consequent reduction in variability happens with experience. Therefore, stage 3 format was used for subsequent assessment and applied in all other surveys for all professions.

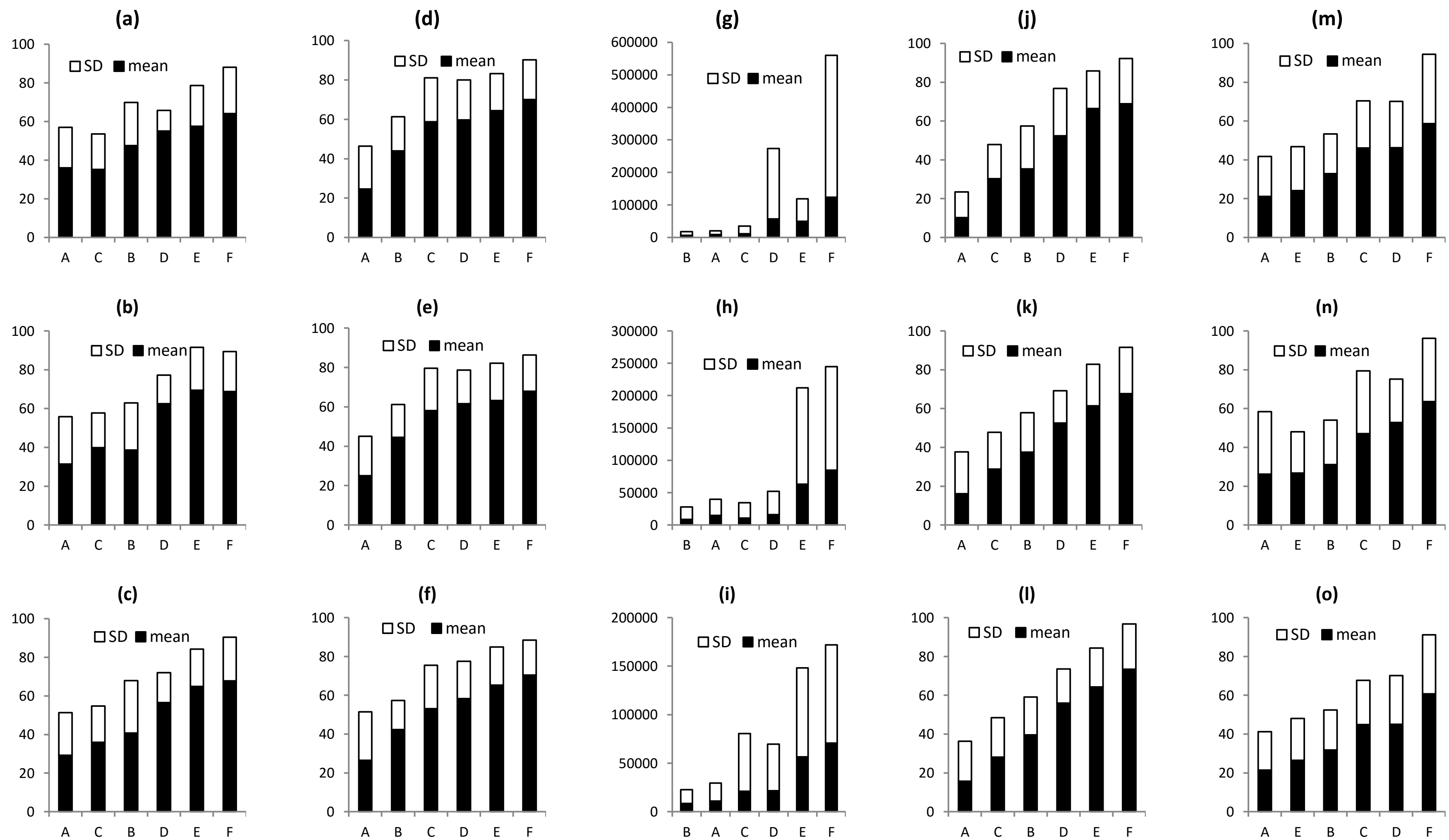


Fig. 5.1: Learning process of estimation by civil engineering students. The variables are expressed in percent (%). A to F represent the picture letters as shown in Figs. 3.3, 3.4 and Appendix E. (a), (b) & (c) are *Aesthetics* stage 1, stage 2 & stage 3 respectively; (d), (e) & (f) are *Land cost* stage 1, stage 2 & stage 3 respectively; (g), (h) & (i) are *Land size* stage 1, stage 2 & stage 3 respectively; (i), (j), (k) & (l) are *Habitat for species* stage 1, stage 2 & stage 3 respectively; (m), (n) & (o) are *Safety* stage 1, stage 2 & stage 3 respectively.

Table 5.1.: Summary of the questionnaire analysis* for the civil engineering student cohort.

Picture number	Target score	Stage 1		Stage 2		Stage 3	
		Mean	STDEV[a]	Mean	STDEV[a]	Mean	STDEV[a]
Aesthetics (%), which is part of variable 16 (*Aesthetics, education, culture and art*; Table 3.3)							
1	30	36	20.9	29	22	31	24.4
2	43	35	18.3	36	18.8	40	17.8
3	49	48	22.4	41	27.2	39	24.2
4	62	55	10.6	57	15.5	63	14.8
5	74	58	21.1	65	19.4	69	22.2
6	82	64	23.9	61	22	69	20.5
Land size (m^2), which influences all variables (Table 3.3)							
1	3240	6370	11,613	8510	19,523	8400	14,302
2	4600	8540	11,621	14,630	25,144	10,990	18,423
3	8200	11,560	23,187	10,790	23,532	21,100	59,486
4	9440	57,010	216,610	16,040	35,940	21,690	48,024
5	10,350	49,520	69,104	63,160	149,055	56,650	91,580
6	70,000	123,470	436,125	84,940	159,947	70,790	101,090
Land cost (%), which is part of variable 15 (*Tourism and area value*; Table 3.3)							
1	27	27	24.9	25	20	25	21.9
2	35	42	15	45	17.7	44	17.4
3	54	53	22.4	58	21.6	59	22.4
4	60	58	19.3	62	17.1	60	20.3
5	69	65	19.7	63	19	64	18.9
6	78	71	17.9	68	18.5	70	20.2
Habitat for species (%), which is variable 1 (Table 3.3)							
1	9	10	13.2	16	21.5	16	20.6
2	23	30	17.5	29	18.9	28	20.4
3	45	35	22	38	20.3	40	19.5
4	62	52	24.4	53	16.7	56	17.5
5	70	67	19.4	62	21.3	64	20
6	82	69	23.2	68	23.8	74	23.3
Safety (%); which is part of variable 14 (*Recreation, and mental and physical health*; Table 3.3)							
1	20	21	20.7	22	20	26	32.2
2	29	24	22.6	27	21.6	27	21.2
3	34	33	20.4	32	20.6	31	22.9
4	40	46	24.3	45	22.8	47	32.3
5	62	46	23.9	45	25.2	53	22.5
6	74	59	35.7	61	30.4	64	32.7

Notes: * indicating the variability for example variables and progressive learning; [a] standard deviation.

5.3. Assessment of the Variability Among the different Professions

Figure 3.4 shows the relative ranking values for the variable *habitat for species* (%) in ascending order (i.e., from highly inadequate to highly adequate habitat).

The example variables *aesthetics*, *land costs* and *habitat for species* (Fig. 3.4) were determined relatively well (Fig. 5.1). In comparison, *safety* was associated with higher but still acceptable estimated errors. This can be explained by the high complexity of these variables. The cohort had serious difficulties in estimating *land size*. Nevertheless, this is not considered to be a problem, because land size can be easily measured in the field or estimated using maps.

Figures 5.2 to 5.4 show the findings for the ecology students, social science students and the general public, respectively. The standard deviations associated with variable estimations were usually lower for the ecology compared to the civil engineering students. In comparison, the same was the case for social science students (except for *aesthetics* and *habitat for species*). The standard deviations for ecology and social science students and the general public were rather similar.

Table 5.2 shows an assessment of the statistically significant differences between different cohorts of estimators for selected SUDS characterization variables using the non-parametric Mann-Whitney U-test. There were five relationships that could be considered as unexpected with respect to commonly hold public opinions. Civil engineering compared to ecology students had similar views regarding *habitat for species* (P = 0.994; Table 5.2) and *safety* (P = 0.494; Table 5.2). However, one might assume that *habitat for species* would be much more important to ecologists than engineers. On the other hand, engineers are usually more aware of health and *safety* matters than ecologists.

Someone might expect that civil engineering and social science students might have different views regarding *habitat for species*. However, the study showed that the data were rather similar (P = 0.379; Table 5.2). It could be expected that ecology students would have a different opinion regarding *habitat for species* compared to the general public. However, their assessments were rather similar (P = 0.072; Table 5.2), which is surprising considering that ecologist should have a better understanding of the associated science and might therefore have different assessment criteria. Finally, social scientists and the general public might be expected to have similar opinions with respect to the estimation of *land costs*. However, their estimations were significantly different (P = 0.006; Table 5.2), which could be explained by the dominance of engineers in the general public sample.

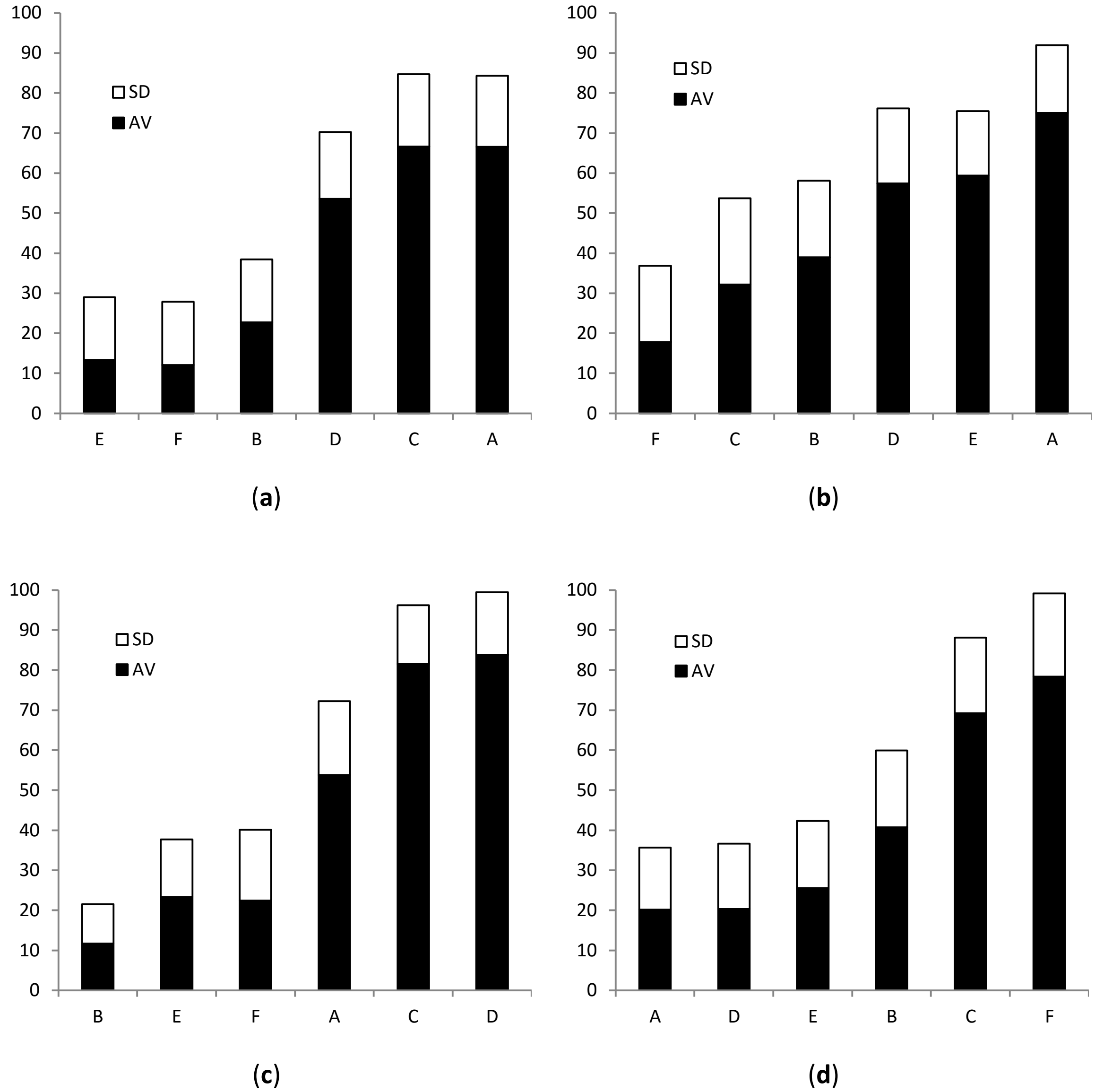


Fig. 5.2: Phase 3 estimations (%) by ecology students for the variables (**a**) *aesthetics;* (**b**) *land cost;* (**c**) *habitat for species;* and (**d**) *safety* based on different pictures, represented by the letters A to F, on the x-axis. SD, standard deviation; AV, average. Letters A-F corresponds to the picture letters as shown in Figs. 3.3, 3.4 and Appendix B.

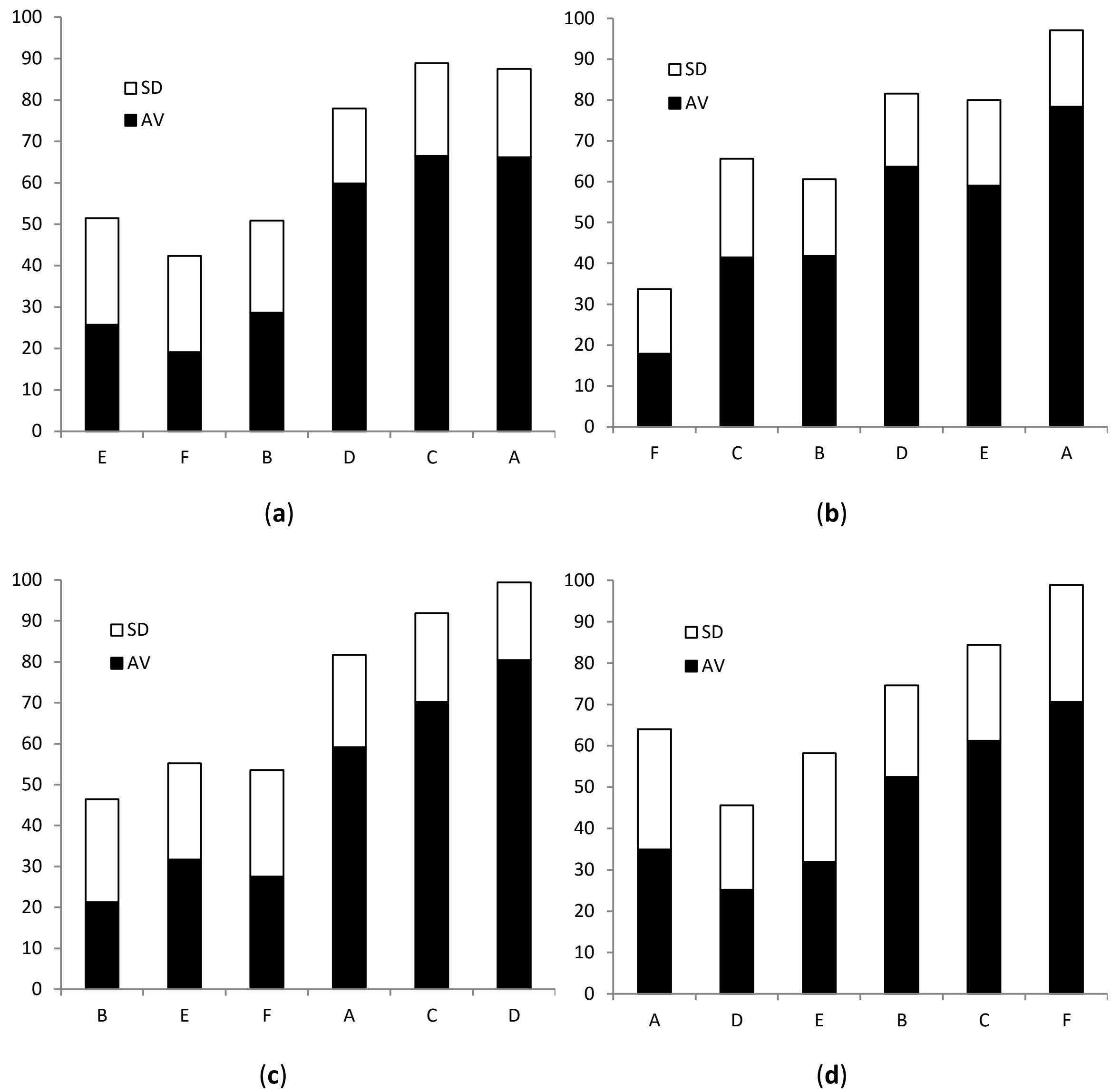


Fig. 5.3: Phase 3 estimations (%) by social science students for the variables (**a**) *aesthetics*; (**b**) *land cost*; (**c**) *habitat for species*; and (**d**) *safety*. based on different pictures represented by the letters A to F on the x-axis. SD, standard deviation; AV, average. Letters A-F corresponds to the picture letters as shown in Figs. 3.3, 3.4 and Appendix B.

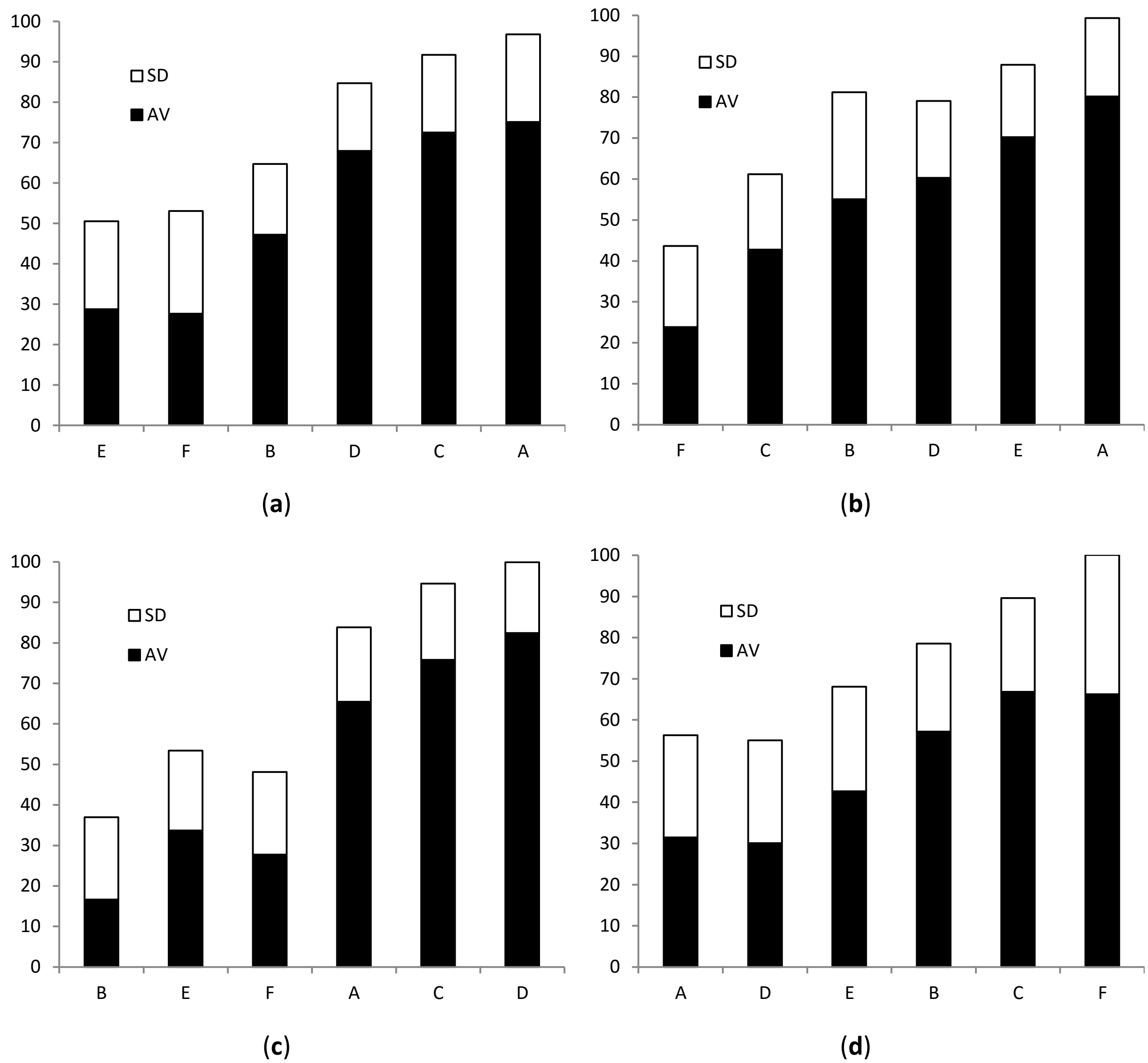


Fig. 5.4: Phase 3 estimations (%) by the general public for the variables (**a**) *aesthetics*; (**b**) *land cost*; (**c**) *habitat for species*; and (**d**) *safety*. based on different pictures represented by letters A to F on the x-axis. SD, standard deviation; AV, average. Letters A-F corresponds to the picture letters as shown in Figs. 3.3, 3.4 and Appendix B.

Table 5.2: Assessment of the statistically significant differences between different cohorts of estimators (civil engineering, ecology and social science students, and the general public) for selected SUDS characterization variables (*aesthetics, land cost, habitat for species* and *safety*) using the non-parametric Mann-Whitney U-test (see also Section 3.3.5).

Cohort comparisons	Statistic	*Aesthetics*	*Land cost*	*Habitat for species*	*Safety*
Civil engineers and ecologists	*P*	0	0.004	0.994	0.494
	H	1	1	0	0
Civil engineers and social scientists	*P*	0.004	0.157	0.379	0.027
	H	1	0	0	1
Civil engineers and the general public	*P*	0.396	0.094	0.05	0.002
	H	0	0	0	1
Ecologists and social scientists	*P*	0.07	0.183	0.5	0.175
	H	0	0	0	0
Ecologists and the general public	*P*	0	0	0.072	0.018
	H	1	1	0	1
Social scientists and the general public	*P*	0.002	0.006	0.311	0.453
	H	1	1	0	0

Notes: *P* value, probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true; H, response indicator; if H = 1, values are statistically significantly different ($P < 0.05$) for the corresponding parameter; if H = 0, the difference is not significant.

5.4. Different Professional Perspectives

Different professions will probably want to assign a higher importance to those variables that are of greater relevance to their interests (Table 3.4 and 5.3). Therefore, the new tool takes into account the diversity of professional opinions by giving any user the opportunity to select a weighting system (Table 3.4) of greatest relevance to his or her line of thought. However, the introduction of associated bias can be avoided by not selecting any weighting system.

The findings in Section 5.2 can be used to adjust the estimation results for related cohorts. For example, if an estimation is made by cohort A for a variable *x*, and it is known that A consistently overestimates *x* by 10% compared to all other relevant cohorts, *x* could be reduced by 10%, which would result in an estimation more acceptable by the majority of stakeholders. With respect to this study, the general public sample is dominated by engineers (at least 43%; Sections 3.3.2 and 3.3.3). Considering that engineers consistently overestimate *aesthetics* for less beautiful (<50% for aesthetics) SUDS sites in comparison to, for example, ecologists and social scientists (Table 5.1; Figures 5.1, 5.2 and 5.3), their estimations could be reduced by at least 15% and 5%, respectively, to bring them in line with those made by ecologists and social scientists. Such relationships can be formalized in numerical models based on uncertainty estimations associated with different cohorts and variables (Resfgaard, et. al., 2007).

5.5. Findings of the Assessment Method

As discussed in chapter 4, the presence of public parks did not increase the overall suitability of retrofitting sites, because they were usually small in size (30% of sites were <25,000 m^2), low in tree coverage (7%) and the presence of surface water [stream (0%), river (11%), canal (21%) and standing water (8%)] of the associated catchment was limited (as mentioned in chapter 4). However, the introduction of a weighting system (Table 3.4) that puts bias towards what a drainage engineer would perceive as more important variables for SUDS (e.g., flood control as part of *MEE* and water quality control considered by SRT) could increase the suitability of sites for retrofitting.

Table 5.3 shows the assessment approach in terms of proposed SUDS techniques for Greater Manchester. The relative proportions for each SUDS technique have been expressed in percentage points for all selected professions. Note that there were many occasions where more than one SUDS technique had the same order of preference.

Table 5.3: Comparison of assessment approaches for the proposed sustainable drainage system (SUDS) techniques (Greater Manchester case study)

SUDS Technique	Proportion (%) of sites at which SUDS techniques are given first, second or third order of preference for the …								
	… community & environment approach …			… ecosystem service approach…			… combined approach …		
	First	Second	Third	First	Second	Third	First	Second	Third
… from the perspective of a **drainage engineer** when applying the corresponding weights shown in Table 3.4									
Permeable pavement	30	18	16	43	9	4	31	14	13
Filter strip	13	23	27	2	7	12	14	19	16
Swales	0	6	9	0	2	12	0	1	10
Green roof	0	1	12	0	0	3	0	0	0
Pond	14	11	17	33	11	4	31	4	4
Constructed wetland	8	2	14	11	1	2	3	6	1
Infiltration trench	23	35	20	5	9	44	16	28	27
Soakaway	61	20	12	0	4	15	16	44	18
Infiltration basin	0	3	17	1	4	8	0	1	8
Belowground storage	33	14	8	5	44	13	4	28	13
Water playground	2	4	18	3	17	9	1	2	2
… from the perspective of a **developer** when applying the corresponding weights shown in Table 3.4									
Permeable pavement	31	17	17	42	13	12	29	12	13
Filter strip	11	14	31	11	23	14	13	25	15
Swales	1	5	18	1	13	11	0	0	5
Green roof	1	1	13	0	0	1	0	0	0
Pond	25	10	19	36	9	1	41	3	1
Constructed wetland	9	1	16	8	6	1	2	5	2
Infiltration trench	21	25	27	2	32	23	9	20	34
Soakaway	53	34	8	3	1	34	8	29	38
Infiltration basin	1	5	16	1	1	8	0	1	5
Belowground storage	33	16	11	0	11	23	6	27	11
Water playground	3	12	22	1	2	6	1	6	6
… from the perspective of an **ecologist** when applying the corresponding weights shown in Table 3.4									
Permeable pavement	32	12	15	39	7	12	38	8	9
Filter strip	6	17	38	13	22	22	16	24	17
Swales	1	8	22	2	13	22	0	3	15
Green roof	0	1	17	0	1	2	0	0	0
Pond	37	8	15	30	13	5	40	5	0
Constructed wetland	8	7	15	10	1	3	5	9	0
Infiltration trench	13	22	28	8	33	26	5	26	26
Soakaway	36	29	13	1	8	17	5	30	31
Infiltration basin	0	8	18	2	8	12	0	0	12
Belowground storage	28	16	7	1	13	32	3	26	12
Water playground	4	13	26	5	19	8	1	10	9
… from the perspective of a **planner** when applying the corresponding weights shown in Table 3.4									
Permeable pavement	30	19	13	39	8	6	28	15	12
Filter strip	11	18	30	8	11	29	18	23	16
Swales	0	5	19	1	6	17	0	1	4
Green roof	0	1	13	0	1	1	0	0	0
Pond	21	12	16	31	12	1	35	6	4
Constructed wetland	8	2	17	10	1	1	3	6	1
Infiltration trench	22	23	27	0	6	25	10	20	33
Soakaway	56	27	9	0	3	16	9	28	40
Infiltration basin	0	5	18	0	2	9	0	0	6
Belowground storage	32	15	9	5	42	14	6	26	12
Water playground	1	8	20	5	19	7	1	3	2

… from the perspective of a **social scientist** when applying the corresponding weights shown in Table 3.4									
Permeable pavement	30	17	14	39	7	6	29	11	12
Filter strip	10	19	31	12	24	19	19	23	15
Swales	0	5	18	0	1	11	0	0	9
Green roof	0	1	11	0	1	0	0	0	0
Pond	20	14	14	33	10	0	39	5	1
Constructed wetland	8	4	14	10	0	1	3	7	0
Infiltration trench	21	26	24	0	9	31	9	16	33
Soakaway	54	27	11	0	2	20	5	24	39
Infiltration basin	0	5	13	0	2	3	0	2	5
Belowground storage	32	11	8	2	33	18	8	29	9
Water playground	1	5	20	5	20	5	1	3	7

Note that there were many occasions where more than one SUDS technique had the same order of preference Note: * Proportion (%) of sites at which sustainable drainage system techniques are given first, second or third order of preference based on different professional perspectives (weights in Table 3). Note that numbers not necessarily add-up to 100, because some techniques received the same preferences.

Table 5.4 shows a comparison of the inter-site variability for a given sustainable drainage technique for Greater Manchester, and helps to interpret the preference distributions in Table 5.3. As discussed in chapter 4, Ponds are associated with the greatest inter-site variability because of their potentially relatively small size and great popularity (Scholz, 2010; Scholz, 2006; Scholz, 2004).

The inter-site variability for Green roof was consistently zero across all professions under traditional ‘community and environment’ and ‘combined’ approaches (Table 5.4). The reason for this could either be that green roof could not be easily related to the variables representing ‘community and environment’ and ‘combined’ approaches, or that in most sites, there were no future plan for building structures that could incorporate green roofs. This was also the case with Table 4.3.

It may come as a surprise that permeable pavements scored relatively highly on ecosystem service variables (Table 5.3), which contradicts the common belief among some engineers that there has to be a strong bias towards natural and soft techniques when using ecosystem service assessment techniques (Scholz, 2010; Butler and Davies, 2004). However, permeable pavements are likely to attract high values for variables such as *SRT* and *MEE*, respectively, if properly designed and managed.

5.6. Effects of the weighting factors

The proposed professional weightings introduced in Table 3.4 were applied to the raw data collected from the 100 potential retrofitting sites, and used to compute the SUDS retrofitting options for ‘community and environment’, ‘ecosystem service’ and ‘combined’ approaches (see Table 5.3).

After applying the weighting factors, all techniques consistently maintained similar patterns of variation under ecosystem service approach across all professions (Table 5.4). Therefore comparing the inter-site variability using standard deviation for ‘ecosystem service’ approach only against the different professions (Table 5.4), it could be observed that the weighting system seemed to have unified the assessment to follow similar patterns irrespective of the professional differences in assessments. Therefore the proposed weights served as adjustment factors against wide views of different stakeholders. This trend was also observed in the ‘community and environment’ and the ‘combined’ approaches except for the Ecologist. This could be interpreted to mean that the weighting factors may not have had much influence on the Ecologists when the ‘community and environment’ and ‘combined’ approaches were applied. This further strengthens the case for the adequacy of ‘ecosystem service’ approach, and hence its introduction to the decision support tools for the retrofitting of SUDS techniques.

Under ‘community and environment’ approach, soackaway and belowground storage dominated the first choice for all the professions (Table 5.3) but ranked low under ‘ecosystem service' and 'combined' approaches. However for ecosystem service approach, permeable pavements and ponds dominated the first choice techniques for all professions (Table 5.3), this may have been contributed hugely due to high aesthetic values of permeable pavements and ponds in city centres and residential areas.

There seemed to be consistency in the choice of the retrofitting SUDS techniques across all the professions for each specific approach indicating that the weighting factors purely reflected each profession appropriately.

5.6.1. The Drainage Engineer

Applying the weighting factors using the drainage engineer perspectives increased the preference choice of permeable pavements unto first positions under the ecosystem services approach (comparing Tables 5.3 with 4.2). It also increased the preference choice for belowground storage under ecosystem service storage. However, under traditional 'community and environment' approach, the drainage engineer's preferences for ponds were decreased while that of soakaway increased (Table 5.3). From the drainage engineer perspective, permeable pavements ranked 2nd in the choice of SUDS techniques under 'community and environment' approach, while soakaway ranked 1st indicating a preference for source control of precipitation over permeable pavements. Swales, green roof and infiltration basin never came as first choice under 'community and environment' approach. However, under 'ecosystem service variables' and 'combined' approach, permeable pavements ranked 1st in the choice of SUDS techniques for retrofitting. Therefore ecosystem service variables favours permeable pavements more and in preference to other flooding source control techniques.

5.6.2. The Developer

From the developer's point of view, there were more significant changes in the preference options under ecosystem service approach after applying the weighting factors for a developer (Table 5.3 compared with Table 4.2). There were less significant changes in the preference options under the traditional 'community and environment' and the 'combined' approaches (Table 5.3 and 4.2). From the Developer perspective, Soakaway ranked the highest choice followed by belowground storage and permeable pavement under 'community and environment' (Table 5.3). Under ecosystem service approach, permeable pavements had the highest number of 1st preference followed by pond, while in 'combined' approach, pond ranked the highest number of 1st preferences. This trend of preferring more of ponds over permeable pavements was consistent with ecologists, planners and social scientists, except for drainage engineer.

5.6.3. The Ecologist

After applying the weighting factors for an ecologist, there were lot of significant changes in the preference options of the SUDS techniques under the ecosystem service approach (comparing Table 5.3 with Table 4.2), indicating a thorough adjustment effect of the weighting factors under ecosystem service approach. There were less significant changes in the preference options under the traditional 'community and environment' and the traditional approaches. Permeable pavements consistently featured a high preference options by the ecologist in all the three approaches (Table 5.3). There was a significant increase towards the 1st preference options for permeable pavements and infiltration trenches under the 'ecosystem service' approach (Table 5.3).

Under ecologist (Table 5.4), the mean and standard deviation of all SUDS techniques were consistently smallest under ecosystem service approach except for green roof. The mean and standard deviation for green roof were zero under the traditional ‘community and environment’ and ‘combined approaches, but were 1 and 6 respectively under ecosystem service approach, indicating a proper and expected reflection of an ecologist.

5.6.4. The Planner

After applying the weighting factors of the Planners, the highest number of significant changes in the preference options of the SUDS techniques occurred under the ‘ecosystem service’ approach, followed by that of the traditional ‘community and environment’ approach, and then the ‘combined’ approach (comparing Table 5.3 with Table 4.2). Under ‘ecosystem service’ approach, there was increase in the permeable pavement options towards the 1st position, and filter strip towards the 3rd positions.

5.6.5. The Social Scientist

After applying the weighting factor for the social scientist, there were lots of significant changes in the preference options of the SUDS techniques in both the ‘ecosystem service’ and the ‘community and environment’ approaches and a minor significant change in the ‘combined’ approach (comparing Table 5.3 with Table 4.2). Under the ‘ecosystem service’ approach, there were a decrease in the third choice options for all the SUDS techniques, but the number of 1st choice options for permeable pavements increased from 34 to 39, (comparing Table 5.3 with Table 4.2) indicating a more precise assessment in the use of ‘ecosystem service’ approach compare to other approaches, which also encouraged the choice for permeable pavements.

Table 5.4: Comparison of the inter-site variability for a given sustainable drainage technique.

SUDS Technique	Standard deviations (based on relative percentage points awarded)					
	Community and environment approach		Ecosystem services approach		Combined approach	
	Mean	**SD**	Mean	**SD**	Mean	**SD**
Perspective of a **drainage engineer**						
Permeable pavement	57	**33**	23	**21**	43	**26**
Filter strip	50	**35**	20	**16**	41	**26**
Swale	31	**27**	14	**15**	28	**19**
Green roof	0	**0**	1	**5**	0	**0**
Pond	32	**37**	28	**31**	31	**34**
Constructed wetland	24	**30**	7	**21**	24	**21**
Infiltration trench	78	**21**	27	**13**	56	**16**
Soakaway	12	**12**	7	**7**	8	**13**
Infiltration basin	51	**27**	24	**13**	38	**19**
Belowground storage	24	**37**	12	**17**	17	**27**
Water playground	68	**31**	23	**18**	53	**23**
Perspective of a **developer**						
Permeable pavement	53	**31**	28	**17**	38	**24**
Filter strip	45	**32**	25	**18**	38	**24**
Swale	29	**25**	20	**17**	26	**18**
Green roof	0	**0**	0	**0**	0	**0**
Pond	36	**41**	33	**36**	33	**37**
Constructed wetland	21	**30**	15	**25**	22	**21**
Infiltration trench	72	**19**	31	**9**	50	**14**
Soakaway	12	**11**	10	**5**	8	**12**
Infiltration basin	47	**23**	21	**16**	34	**18**
Belowground storage	25	**34**	13	**15**	18	**24**
Water playground	61	**32**	30	**17**	47	**24**
Perspective of an **ecologist**						
Permeable pavement	34	**20**	17	**16**	27	**16**
Filter strip	30	**22**	21	**19**	28	**16**
Swale	22	**20**	14	**17**	22	**13**
Green roof	0	**0**	1	**6**	0	**0**
Pond	37	**42**	29	**33**	34	**37**
Constructed wetland	16	**30**	7	**23**	18	**25**
Infiltration trench	45	**12**	24	**13**	34	**9**
Soakaway	12	**7**	8	**9**	10	**7**
Infiltration basin	30	**18**	19	**12**	23	**12**
Belowground storage	19	**21**	11	**13**	14	**16**
Water playground	39	**24**	23	**17**	32	**19**
Perspective of a **planner**						
Permeable pavement	53	**31**	21	**19**	38	**23**
Filter strip	46	**32**	21	**19**	39	**24**
Swale	29	**25**	14	**17**	26	**17**
Green roof	0	**0**	1	**5**	0	**0**
Pond	35	**40**	28	**32**	32	**36**
Constructed wetland	21	**30**	7	**21**	22	**22**
Infiltration trench	72	**19**	25	**12**	50	**14**
Soakaway	12	**11**	7	**6**	8	**12**
Infiltration basin	47	**24**	21	**12**	34	**18**

Table 5.4 contd.						
Belowground storage	24	**34**	13	**15**	18	**24**
Water playground	61	**31**	22	**19**	47	**23**
Perspective of a **social scientist**						
Permeable pavement	51	**30**	18	**16**	36	**22**
Filter strip	45	**32**	21	**18**	37	**22**
Swale	29	**25**	12	**13**	26	**16**
Green roof	0	**0**	1	**5**	0	**0**
Pond	35	**39**	27	**31**	31	**35**
Constructed wetland	21	**30**	6	**19**	22	**21**
Infiltration trench	70	**18**	23	**11**	47	**13**
Soakaway	12	**11**	7	**5**	8	**10**
Infiltration basin	46	**24**	18	**11**	32	**16**
Belowground storage	23	**33**	13	**13**	17	**23**
Water playground	60	**29**	20	**20**	44	**23**

5.7. Chapter summary

The results of the introduction of weighting systems that reflect the different professions of a stakeholder such as the engineers, the developers, the ecologists, the planners and the social scientists, were discussed.

Statistically significant differences between different cohorts of estimators for selected SUDS characterization variables using the non-parametric Mann-Whitney U-test were not found for about half of the possible combinations of cohorts. However, there were four of these relationships that could be considered as unexpected with respect to commonly hold public opinions. Civil engineering compared to ecology students had similar views regarding *habitat for species* and *safety*. Someone might also expect that civil engineering and social science students might have different views regarding *habitat for species*. However, the study showed that the data were rather similar. It could also be expected that ecology students would have a different opinion regarding *habitat for species* compared to the general public. However, their assessments were rather similar.

In comparison, statistically significant differences between cohorts for SUDS characterization variables using the non-parametric test that were surprising, were only found for social scientists compared to the general public, where someone might expect similar opinions concerning the estimation of *land costs*. However, corresponding estimations were significantly different.

CHAPTER 6

TREES AND STRUCTURAL DAMAGE: RESULTS AND DISCUSSION

6.1. Overview

This chapter discusses the damaging effects of existing mature trees with particular focus on permeable pavements and other road structures, and also the public acceptance and values placed on the most prevailing and most damage-causing tree species. Section 6.2 discusses the general tree occurrence data. Section 6.3 focuses on the types of urban structure and their associated damage caused by tree species, and also on the severity of the damage. Section 6.4 analyses the damage with respect to tree diameter (DBH) and distance of trees away from the structures. Section 6.5 discusses specific characteristics of each tree species with regard to the structures studied. Section 6.6 discusses the general perception and public acceptability of some frequent tree species

The results discussed in this chapter, including figures and tables, already formed part of the paper sent for publication (under review) titled "Assessment of tree damage to permeable pavements and other urban structures" on page viii

6.2. General Tree Occurrence Data

70% of the sites had trees in them and were assessed. The remaining 30% were not assessed either because there were no trees in them or because they were not accessible due to being inside private properties or restricted areas like railway stations or tracks. There were a total of 536 trees assessed, of 34 genera and 69 species. Investigations showed that 349 (65%) of these trees caused damage of varied severity to various structures located nearby. Some of the assessed trees were located in Parks with no structures around, and that may have reduced the proportion of trees that caused damage. 44% of all damage occurred on impermeable pavements while about 22% occurred on permeable pavements, which may mean that there are more impermeable pavements than permeable pavements (especially in parks and roads) in Greater Manchester, indicating the need for more retrofitting of Sustainable Urban Drainage System (Uzomah, et. al., 2014). Buildings were the least affected with 0% damage. This value for building may not have reflected accurately as the assessments were only an external visual assessment. An internal structural assessment may reveal more damage to buildings.

After applying the three criteria given in section 3.4.3, the tree species percentage occurrence reduced from the one shown in Fig. 6.1 to the following: Norway Maple (*Acer platanoides*), 13.6%; Sycamore (*Acer pseudoplatanus*) 9.3%; Common Ash (*Fraxinus excelsior*), 8.2%; Wild Cherry (*Prunus avium*), 7.5%; Largeleaved Lime (*Tilia platyphylos*) 7.1%; Horse Chestnut (*Aesculus hippocastanum*), 6.9%; Small-leaved Lime (*Tilia cordata*), 5.2%; Silver Birch (*betula pendula*), 4.7%; Common Hawthorn (*Crataegus monogyna*), 3.5%; and Beech (*Fagus sylvatica*), 2.2%.

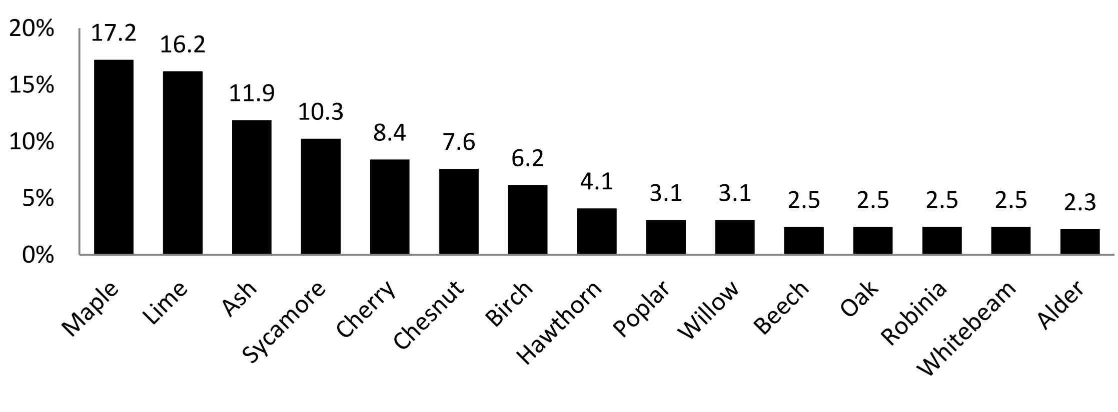


Fig. 6.1: Tree occurrence data. Trees shown here are trees that occurred at least 10 in total, and in a spread of at least 5 sites.

6.3. Structural Damage

The structures that were linked to the most damage from trees were found in the following order: (a) impermeable pavements (44%); (b) permeable pavements (22%); and (c) Kerbs (19%); (Fig. 6.2). The pattern of higher damage assigned for impermeable pavements compared to permeable pavements is in line with the findings by Randrup et al. (2003).This suggests the need for more retrofitting of robust SUDS techniques (Uzomah et al., 2014). Figure 6.3 shows the current severity of damage. However, it is expected that damage will advance further with time.

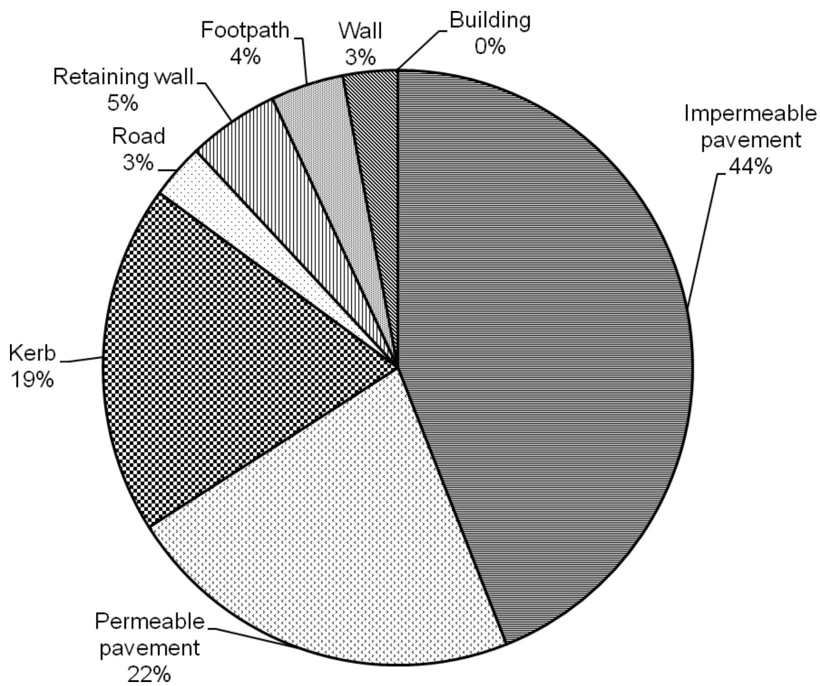


Fig. 6.2: Percentage of damage per structure type.

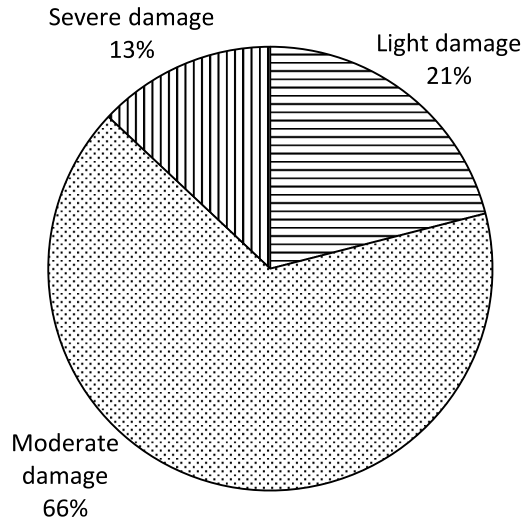


Fig. 6.3: Severity of damage on all structures by percentage.

No damage to buildings was recorded. This is possibly due to the fact that the assessment was only based on an external visual observation. An internal structural assessment may reveal damage to buildings. Moreover, most buildings have formidable foundations and may not be easily damaged as compared to road structures and pathways.

About 52% of all Norway Maples caused various kinds of damage to urban structures. The proportions of the other species that caused damage were as follows: Horse Chestnut, 59%; Large-leaved Lime, 53%; Common Ash, 45%; Sycamore, 42%; Small-leaved Lime, 36%; Beech, 33%; Silver Birch, 32%; Wild Cherry, 15%; and Common Hawthorn, 11%. The severity of corresponding damage was in the following order: moderate (66%); light (21%); and severe (13%) (Fig. 6.3).

There were no definite patterns of damage to structures. This could be attributed to differences in soil moisture content, levels of structural compactions, and average distance of trees from structures. For example, trees are normally planted closer to permeable pavements, impermeable pavements and kerbs compared to roads.

Table 6.1: Moderate and severe damage data for trees that occurred at least 10 times in total, and found in at least 5 different sites.

Species	Common names	Number of occurrence	Percentage occurrence (%)	Number of sites where species is present	Number of species that caused damage	Number of damage on permeable pavement	Number of damage on impermeable pavement	Number of damage on kerb	Number of damage on road	Number of damage on retaining wall	Number of damage on footpath	Number of damage on wall
Acer platanoide	Norway Maple	73	20.0	24	38	10	29	12	2	0	3	3
Acer pseudoplatanus	Sycamore	50	13.7	22	21	9	19	3	1	0	0	1
Fraxinus excelsior	Common Ash	44	12.0	22	20	4	11	8	4	4	1	0
Prunus avium	Wild Cherry	40	10.9	19	6	4	0	1	0	0	2	0
Tilia platyphyllos	Large leaved lime	38	10.4	14	20	7	13	9	0	1	2	0
Aesculus hippocastanum	Horse chestnut	37	10.1	11	22	6	21	6	0	3	0	0
Tilia Cordata	Small leaved lime	28	7.7	14	10	8	2	2	0	0	0	1
Betula pendula	Silver birch	25	6.8	13	8	1	2	2	0	2	1	1
Crataegus monogyna	Hawthorn May	19	5.2	10	2	0	2	0	0	1	0	0
Fagus Sylvatica	Beech	12	3.3	7	4	2	2	2	0	0	1	0
TOTAL		366	100%	156	151	51	101	45	7	11	10	6

***Note:** Please note that some trees caused damage to more than one structure, and as such the addition of the number of damage to all the structures may exceed the number of species that cause damage.

Table 6.2: Tree damage to structures for trees that occurred at least 10 times and found in at least 5 different sites out of the 100 randomly selected sites in Greater Manchester (trees that caused less than 10 structural damage in total are excluded). There were no damage to buildings and no severe damage to Footpaths.

			Acer platanoide	*Acer pseudoplataneus*	*Fraxinus excelsior*	*Prunus avium*	*Tilia platyphyllos*	*Aesculus*	*Tilia cordata*	*Betula pendula*	*Crataegus monoavna*	*Fagus sylvatica*
Damage to Permeable Pavement												
Light			2	3	1	3	2	1	1	0	0	0
Moderate	Number		4	6	3	1	5	5	7	0	0	2
	Distance (m) from structure	Mean	1	0.4	2	2	1	1	1	-	-	0.1
		Standard deviation	1.2	0.5	1.8	0	0.2	0.8	0.8	-	-	0.1
	Diameter (cm) at breast	Mean	54	52	66	-	34	51	26	-	-	68.1
		Standard deviation	3.78	20.5	10.7	-	14.2	18.7	8.58	-	-	28.3
Severe	Number		4	0	0	0	0	0	0	1	0	0
	Distance (m) from structure	Mean	0	-	-	-	-	-	-	0	-	-
		Standard deviation	0	-	-	-	-	-	-	0	-	-
	Diameter (cm) at breast	Mean	58	-	-	-	-	-	-	20	-	-
		Standard deviation	0.48	-	-	-	-	-	-	0	-	-
Damage to Impermeable Pavement												
Light			6	3	4	0	3	3	0	2	0	0
Moderate	Number		18	13	7	0	10	15	0	0	2	1
	Distance (m) from structure	Mean	0	1	1	-	0	1	-	-	1	0.5
		Standard deviation	1	1.4	0.2	-	0	0.2	-	-	0	0
	Diameter (cm) at breast	Mean	41	57	25	-	52	70	-	-	25	89
		Standard deviation	21.5	22.7	8.51	-	8.05	20.5	-	-	0	0
Severe	Number		5	3	0	0	0	3	2	0	0	1
	Distance (m) from structure	Mean	0.04	1	-	-	-	1	0	-	-	0.5
		Standard deviation	0.08	1.4	-	-	-	0.3	0	-	-	0
	Diameter (cm) at breast	Mean	47.7	73	-	-	-	77	38	-	-	89
		Standard deviation	6.75	24	-	-	-	12.1	0	-	-	0
Damage to Kerb												
Light			3	1	1	0	2	2	2	0	0	0
Moderate	Number		6	2	5	1	6	4	0	2	0	0
	Distance (m) from structure	Mean	1	1	1	0	1	1	-	0	-	-
		Standard deviation	0.9	0	0.8	0	1	0.2	-	0	-	-
	Diameter (cm) at breast	Mean	42	64	66	62	48	70	-	45	-	-
		Standard deviation	7.6	0	20.1	0	6.09	26.9	-	27.9	-	-
Severe	Number		3	0	2	0	1	0	0	0	0	2
	Distance (m) from structure	Mean	0	-	1	-	0.3	-	-	-	-	0.3
		Standard deviation	0.1	-	0.9	-	0	-	-	-	-	0.3
	Diameter (cm) at breast	Mean	38	-	36	-	43	-	-	-	-	92.8
		Standard deviation	8.06	-	3.66	-	0	-	-	-	-	3.66
Damage to Retaining Wall												
Light			0	0	0	0	0	0	0	1	0	0
Moderate	Number		0	0	3	0	1	3	0	1	1	0
	Distance (m) from structure	Mean	-	-	0.4	-	0	0	-	0	0.3	-
		Standard deviation	-	-	0.2	-	0	0.2	-	0	0	-
	Diameter (cm) at breast	Mean	-	-	57.5	-	46	61	-	125	20	-
		Standard deviation	-	-	14.1	-	0	8.13	-	0	0	-
Severe	Number		0	0	1	0	0	0	0	0	0	0
	Distance (m) from structure	Mean	-	-	0.1	-	-	-	-	-	-	-
		Standard deviation	-	-	0	-	-	-	-	-	-	-
	Diameter (cm) at breast	Mean	-	-	38	-	-	-	-	-	-	-
		Standard deviation	-	-	0	-	-	-	-	-	-	-
Damage to Footpath (Sidewalk)												
Light			2	0	0	0	0	0	0	1	0	0
Moderate	Number		1	0	1	2	2	0	0	0	0	1
	Distance (m) from structure	Mean	3	-	1	3	0	-	-	-	-	1
		Standard deviation	0	-	0	0	0	-	-	-	-	0
	Diameter (cm) at breast	Mean	63	-	53	49	45	-	-	-	-	89
		Standard deviation	0	-	0	20.8	0	-	-	-	-	0

6.4. Analysis of damage with respect to tree diameter and distance from structure

Figures 6.5, 6.8 to 6.13 show the relationship of tree DBH, distance of trees away from the structures, and the proportion of trees close to structures that caused moderate to severe damage. For *x(y/z)* where *x* represent the DBH in cm, which is also signified by the relative size (diameter) of the circle, *z* represents the number of the tree species within 10 m to the structure, out of which *y* trees caused moderate to severe damage.

In order to achieve maximum ecosystem service and tree benefits, the optimum tree species that could be combined with SUDS is the one that (a) is as close to a structure as possible; (b) has a large diameter; (c) causes the least or no damage; and (d) is readily available and desirable by residents. The closer trees are to the structures or residents, the more the effects are felt, for example, reducing localised extreme temperatures, etc. The larger a tree diameter is, the more matured the tree will be and therefore the higher the tree benefits (Leuzinger, et al., 2010). Trees with least or no damage are usually preferred both for new construction or retrofitting of SUDS sites. Trees that are desirable by residents are usually the ones with higher aesthetic values.

6.4.1. Permeable pavements

Most damage to permeable pavements was caused by trees located within 0 to 1.0 m away from a structure, except for those from Common Ash. About 35% of Common Ash located close to permeable pavements caused damage to these pavements if their average diameter was 66 cm and if their average distance was 2.3 m away from the permeable pavements (Fig. 6.5). The trees with the highest percentage of moderate and severe damage to permeable pavements (up to 50 %) were Beech, Sycamore and Silver Birch. The average distance of Beech and Silver Birch to permeable pavements was 0 m, indicating that most of these two species were planted too close to the pavement. The average DBH of the trees was 68 cm and 20 cm, respectively (Fig. 6.5).

A B

Fig. 6.4: Retrofitting permeable pavements in the presence of mature Norway Maple. A – is the site before retrofitting; B – the site being retrofitted. Photos taken by Vincent Uzomah.

Norway Maple (*Acer platanoide*) caused the most overall damage (2 light, 4 moderate and 4 severe damage) to permeable pavements (Table 6.2). The average diameter of the tree was 56 cm and the average distance from the permeable pavements was 0.8 m. However, Fig. 6.5 shows a comparison for only moderate and severe damage. Seven out of sixteen Small-leaved Lime trees located close to permeable pavements caused major damage. The corresponding average tree diameter was 26 cm and the average distance from the structures was 0.8 m. Sycamore caused six major damage to permeable pavements. The average DBH of this tree was 52 cm and located 0.4 m away from the structure. Large-leaved Lime caused five major damage to permeable pavements. Its average diameter was 34 cm and the corresponding average distance from structures was 0.8 m. For Common Ash, although three major damage to permeable pavements were recorded, the average distance from the structure was 2.3 m and the average diameter was 66.10 cm, indicating that these were mature trees located far from the structure, but still caused damage.

The Beeches assessed were mature trees with an average diameter of 68.12 cm and an average distance of 0 m away from the structures. On the other hand, the Silver Birches were not as mature yet (Table 6.5). Their average DBH was 20.05 cm and they were planted too close to the structures. Silver Birch of this DBH was estimated to be about 20 years of age using the formula developed by and Tkaczyk Tomusiak (2013) (see section 3.4.4). Therefore Beech could be recommended for use with permeable pavements. In addition, Common Beech ranked very high in peoples' acceptance both in spring and autumn (Table 6.7).

Fig. 6.4 shows site 1 being retrofitted with permeable pavement in the presence of mature Norway Maple. However, enough space was given around the tree base. The Norway Maple root as seen in the damage shown in Fig 6.7 was completely dug out before retrofitting.

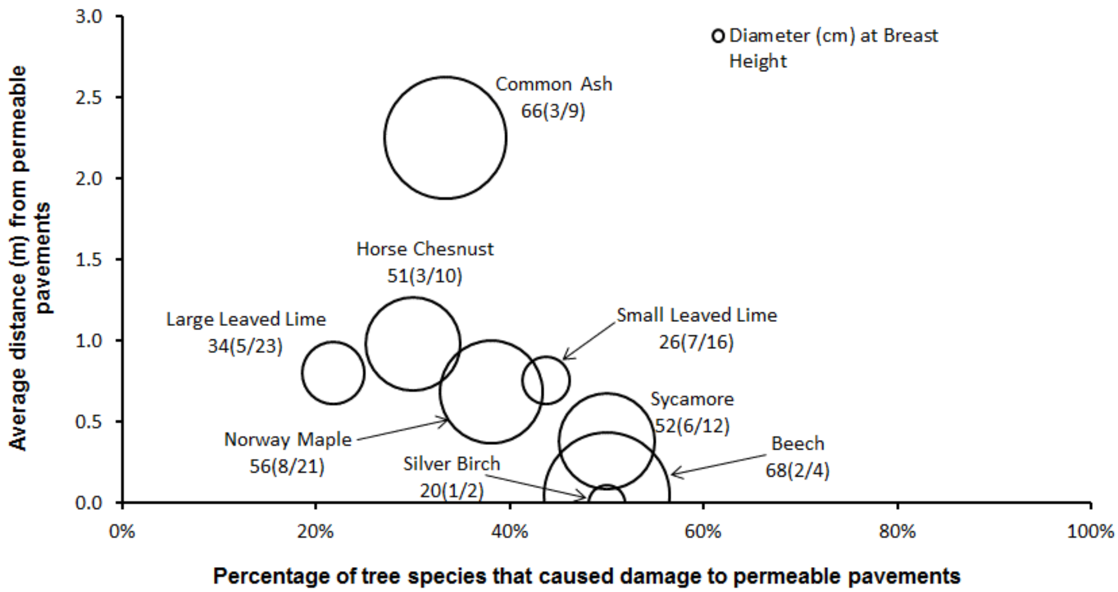


Fig. 6.5: Comparison of tree damage and their average distance to permeable pavements.

Fig. 6.6: Various forms and designs of permeable pavements from example sites. Photos were taken by Vincent Uzomah.

6.4.2. Impermeable pavements

The majority of the damage occurred on impermeable pavements (44%) (Fig. 6.2). The reason for this is that impermeable pavements do not allow free circulation of moisture and air into and out of the pavement surface (Randrup et al., 2003; Day et. al., 2010). Because of this, pockets of moisture build up below the surface of impermeable surfaces causing the roots of trees below the impermeable surface to be attracted to these pockets of moisture, and thereby lifting up the pavement surface. This may have accounted for the relatively high number of damage to impermeable pavements.

For impermeable pavements, the further away the trees are, the higher the percentage that causes damage irrespective of the tree DBH (up to a distance of 1.4 m; Fig. 6.8). This trend further confirms that most tree roots under impermeable pavements tend to go for the pockets of moisture that accumulate underneath the impermeable surface. The further away the impermeable pavement is located from the tree base, the more moisture is expected to accumulate. Wherever tree roots are deprived of air and moisture, they start to grow back towards the surface to obtain them. Morgenroth (2011) studied root distribution in relation to paved and normal surfaces in the top 30 cm of soil. He found that root abundance in the top 30 cm is greater in impermeable pavements than in normal soil.

Fig. 6.7: Some examples of tree roots damage to impermeable pavements of Site 2. Photos were taken by Vincent Uzomah.

Viswanathan et al. (2011) carried out a study concerned with the performance of American Sweetgum (*Liquidambar styraciflua*) tree roots under permeable and impermeable pavements. Their results suggested that the standing live root lengths for the American Sweetgum were longer in impermeable concrete than in permeable concrete for the first 0 to 20 cm of soil depth. Beyond this depth, the standing live roots were more abundant in permeable than in impermeable pavements. However, they concluded that pervious concrete does not give a measurable root production benefit over impervious concrete. However, this study revealed that the sidewalks of Greater Manchester roads consist of more impermeable pavements than permeable pavements. Considering the findings of Morgenroth (2011) and Viswanathan et al. (2011), Greater Manchester case is more likely linked to the phenomenon of insufficient moisture in the compacted soil strata below the impermeable pavements, and the tendency of roots to remain close to the surface for oxygen and moisture availability, and hence the reason for greater damage to impermeable pavements than permeable pavements. This phenomenon seems common where there are more impermeable pavements than porous surfaces.

Sycamore caused the most damage to impermeable pavements (78%) from an average distance of 1.3 m and an average DBH of 64 cm. This is further discussed in section 6.5.4.

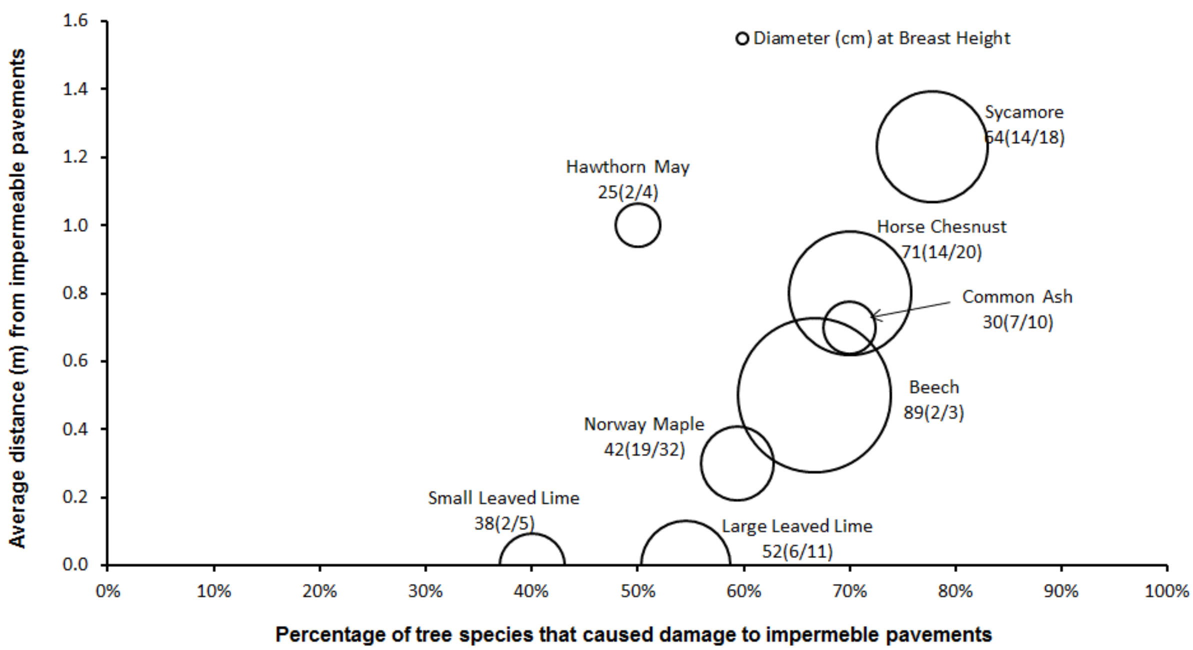


Fig. 6.8: Comparison of tree damage, tree diameters and their average distances to impermeable pavements

6.4.3. Kerbs, Roads, Retaining walls and Footpaths

Kerb damage comprised 19% of all recorded structural damage (Fig. 6.2). Norway Maple caused the most damage to kerbs (10 out of 16 trees were located close to kerbs) from an average distance of 0.6 m and with an average DBH of 41 cm (Fig. 6.9). Similar to Norway Maple was Large-leaved Lime (7 out of 13 nearby Large-leaved Lime trees). Sycamore (2 out of 11 surrounding trees) and Common Ash (7 out of 14 surrounding trees) caused damage to kerbs from the farthest average distance of 1 m (Fig. 6.9). Other trees that caused damage were less than 1 m from the kerb as shown in Fig 6.9. Wild Cherry (*Prunus avium*) was the best tree suitable for kerbs: only 1 in 14 trees caused moderate to severe damage (Fig. 6.9). However, most Wild Cherries were very closely located (0 m) to kerbs, and their average DBH was 62 cm. This was closely followed by Common Beech (*Fagus silvatica*). Although for Common Beech of an average DBH of 93 cm (indicating trees well-advanced in age) and an average distance of 0.23 m from kerbs, only 2 out of 9 trees caused moderate to severe damage to kerbs (Fig. 6.9). The worst tree to be located close to kerbs is Norway Maple. For trees of this species with an average DBH of 41 cm (indicating middle age) and located about 0.6 m from the kerbs, about 10 out of 16 Norway Maples caused moderate to severe damage to kerbs (Fig 6.9).

Percentage of damage to roads and retaining walls were 3 % each. (Fig. 6.2). Only three trees (Common ash (*Fraxinus excelsior*), Norway Maple (*Acer platanoide*) and Sycamore (*Acer pseudoplatanus*)) caused moderate to severe damage to roads (Fig. 6.10). Trees that caused damage to roads were located within an average distance of 2 to 5 m away from roads, indicating that the majority of them were planted close to the sidewalks.

Not many trees were found close to retaining walls. For Silver Birch of 125 cm DBH, planted at an average distance of close to 0 m, only 1 out of 2 trees caused moderate to severe damage (Fig. 6.11). Horse Chestnut caused the most damage to retaining walls. Three out of four Horse Chestnuts with an average DBH of 61 cm and located at an average distance of 0.25 m away caused moderate to severe damage to retaining walls (Fig. 6.11).

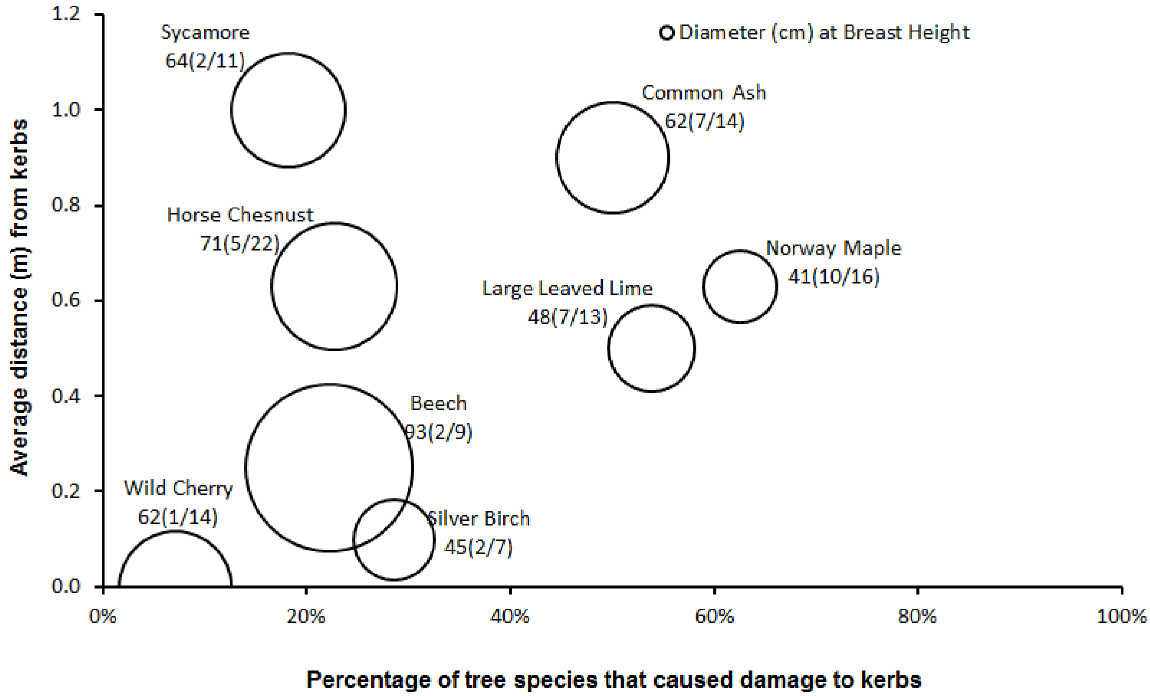


Fig. 6.9: Comparison of tree damage, tree diameters and their average distances to kerbs.

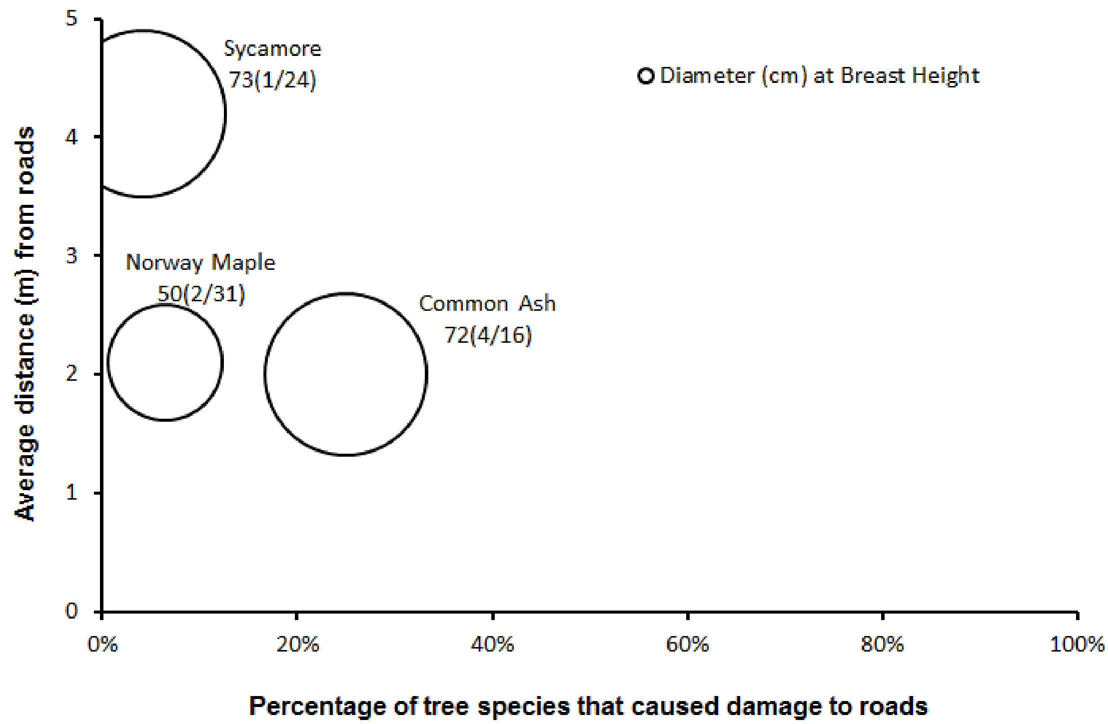


Fig. 6.10: Comparison of tree damage, tree diameters and their average distances to roads.

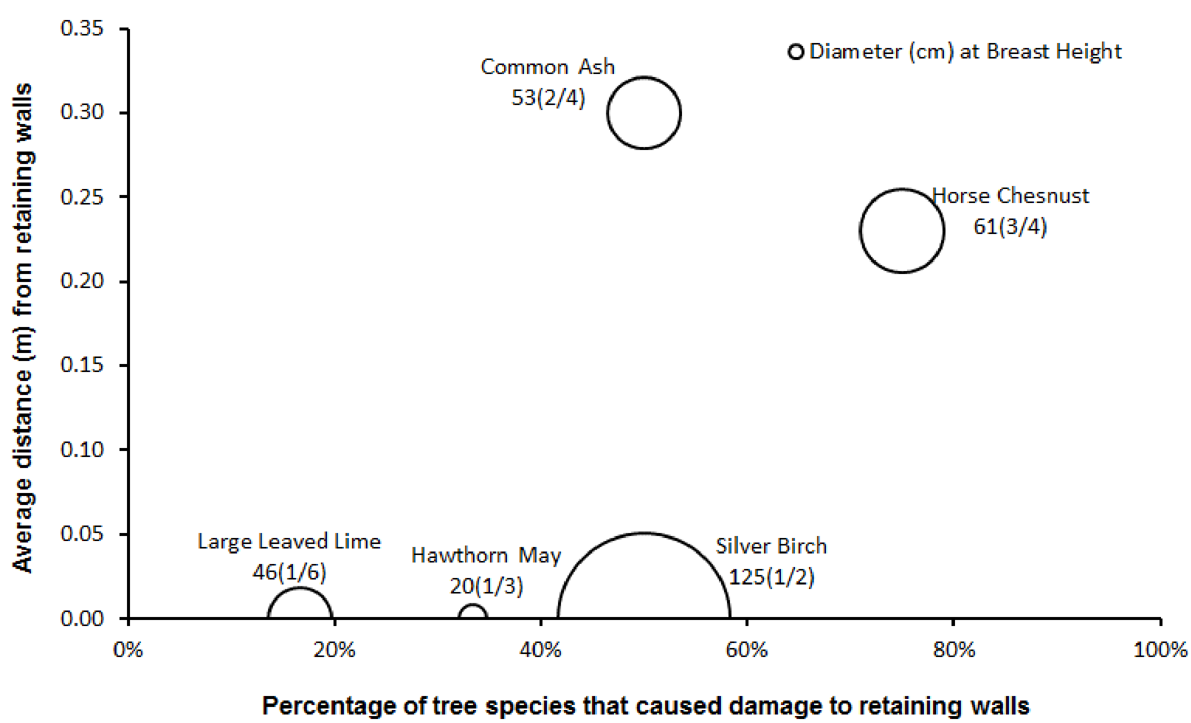


Fig. 6.11: Comparison of tree damage, tree diameters and their average distances to retaining walls.

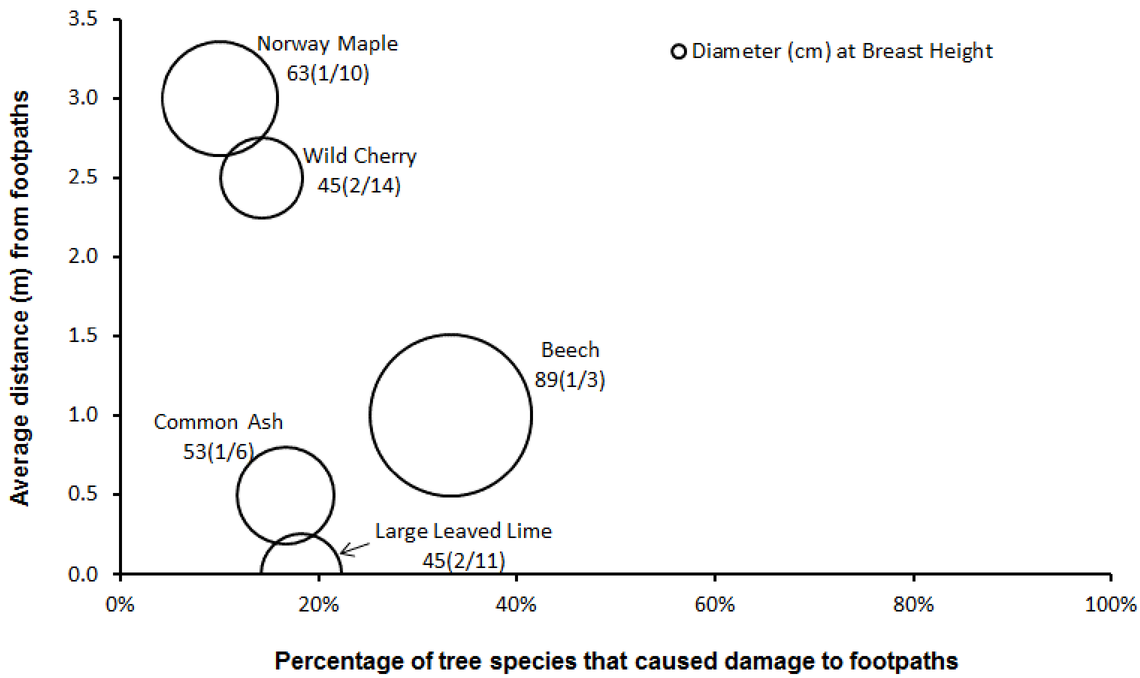


Fig. 6.12: Comparison of tree damage, tree diameters and their average distances to footpaths.

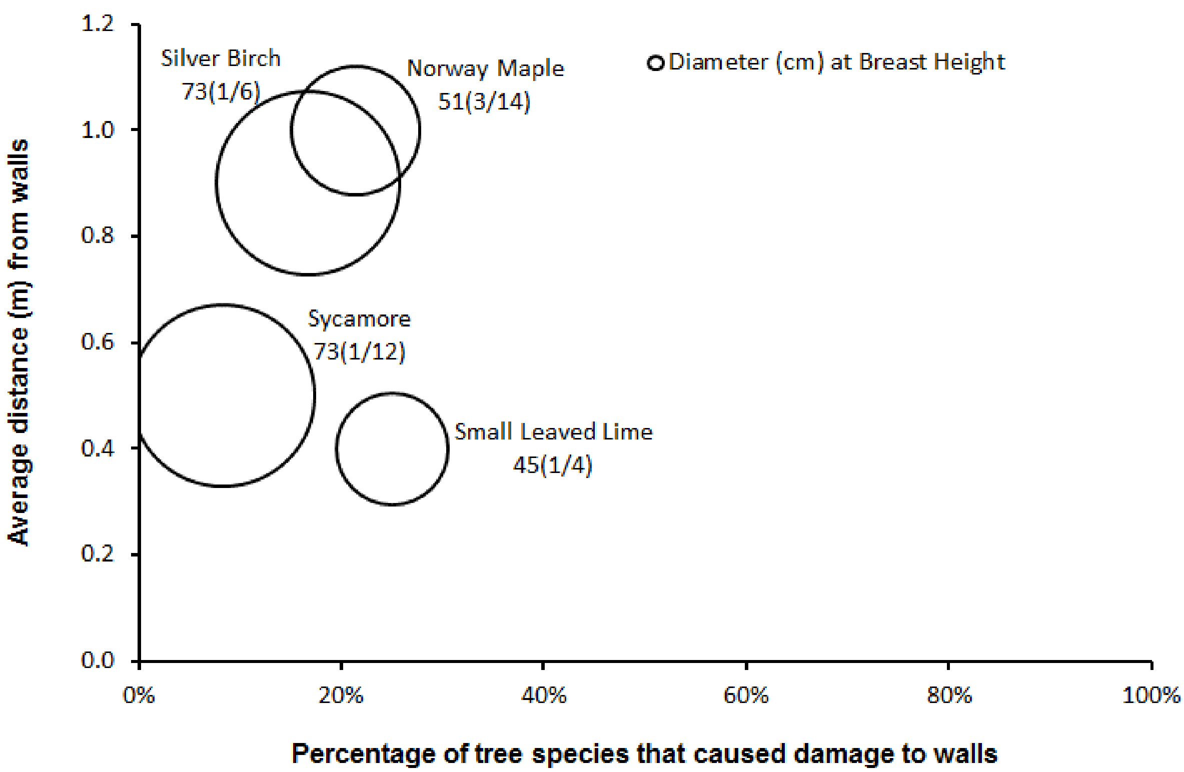


Fig. 6.13: Comparison of tree damage, tree diameters and their average distances to walls.

6.5. The Trees

6.5.1. Norway Maple (*Acer platanoide*)

Norway Maple occurred the most frequently (17%) among other trees that were found in this survey (Fig. 6.1). Furthermore, Norway Maple caused the most severe damage to structures (Tables 6.1 and 6.2). The damage done to structures by Norway Maple did not follow any particular pattern. In this survey, 38 out of 73 (52%) Norway Maples caused damage to various structures (Table 6.1). About 35% of all Norway Maples planted close to permeable pavements with an average DBH of 56 cm and an average distance of 0.75 m from the permeable pavements caused severe to moderate damage to the pavement structures. This average DBH represents a maturing Norway Maple. On average, Norway Maple caused more damage (42%) to impermeable pavements than to permeable pavements. These 42% of Norway Maples had an average DBH of 42 cm with an average distance of 0.3 m from impermeable pavements. This DBH represents a growing Norway Maple. This indicates that Norway Maple has a greater potential to cause more damage to impermeable pavements than to permeable pavements.

About 60% of Norway Maples with an average DBH of 41 cm caused severe to moderate damage to kerbs from an average distance of 0.6 m. Norway Maples of this DBH are still in the growing stage, indicating a future potential to cause more damage to kerbs. It follows that Norway Maple should not be recommended for planting near kerbs, as it is ranked the least suitable tree for planting close to kerbs (Table 6.3). Only 7% of Norway Maple with an average DBH of 50 cm caused severe and moderate damage to roads. Their average distance from roads was 2.0 m. Roads are normally well-compacted during construction to bear heavy traffic and haulage loads, and will therefore resist most damage from tree roots. Moreover, trees are normally located at least 2.0 m from roads, because of spaces for permeable or impermeable pavements and kerbs. Therefore, roads were linked to less damage by tree roots. There were no records of severe and moderate damage to retaining walls by Norway Maples. About 20 % of Norway Maples planted close to walls of average DBH of 51 cm caused severe and moderate damage to these wall structures. Those that caused damage were placed at an average distance of 1.0 m from the walls. About 10% of Norway Maples close to footpaths with an average DBH of 63 cm caused severe and moderate damage to footpaths. Those that caused damage were at an average distance of 3 m to the footpaths. Damage to footpaths by Norway Maple even at a distance of 3 m are possible, because the underlying soils at footpaths are not as compacted as those associated with other road structures. Despite that Norway Maple caused the most damage, and was also ranked the lowest in the potential for retrofitting (Table 6.4), it scored the highest for aesthetics in spring and summer (Table 6.7).

Fig. 6.14: Some selected pictures of Norway Maple taken at Sample sites. All photos taken by Vincent Uzomah.

Table 6.3: Proportion of tree species that caused structural damage

STRUCTURES / TREES	Impermeable pavements	Permeable pavements	Kerbs	Roads	Retaining walls	Foot-paths	Buildings
Norway Maple (*Acer platanoide*)	19/32	8/21	10/16	2/31	0/0	1/10	0/8
Sycamore (*Acer pseudoplatanus*)	14/18	6/12	2/11	1/24	0/4	0/13	0/2
Common Ash (*Fraxinus excelsior*)	7/10	3/9	7/14	4/16	2/4	1/6	0/3
Wild Cherry (*Prunus avium*)	0/6	1/15	1/14	0/13	0/2	2/14	0/2
Large leaved lime (*Tilia platyphyllos*)	6/11	5/23	7/13	0/22	1/6	2/11	0/8
Horse chestnut (*Aesculus hippocastanum*)	14/20	3/10	5/22	0/21	3/4	0/2	0/0
Small leaved lime (*Tilia Cordata*)	2/5	7/16	0/10	0/8	0/5	0/1	0/1
Silver birch (*Betula pendula*)	1/14	1/2	2/7	0/12	1/2	0/5	0/3
Hawthorn May (*Crataegus monogyna*)	2/4	0/0	0/4	0/4	1/3	0/3	0/3
Beech (*Fagus Sylvatica*)	2/3	2/4	2/9	0/3	0/1	1/3	0/3

Table 6.4: Present relative tree-rankings against the structural damage. Notes: RR – Relative rankings; WR – Weighted rankings. The rankings go in increasing order of 'potential for damage', where 1 represents least potential for damage (or best suitable) whereas 10 represents highest potential for damage (or least suitable). Weighting factors reflect the importance of structures (relative importance).

STRUCTURES / TREES	Impermeable pavements (Weight = **5**)		Permeable pavements (Weight = **7**)		Kerbs (Weight = **4**)		Roads (Weight = **8**)		Retaining walls (Weight = **4**)		Footpaths (Weight = **4**)		Buildings (Weight = **10**)		OVERALL RELATIVE TREE RANKING [(Total WR) ÷ (Total RR)]	Best tree ranking
	RR	WR	RR	WR	RR	WR	RR	WR	RR	WR	RR	WR	RR	WR		
Norway Maple (*Acer platanoids*)	6	30	5	35	10	40	3	24	NA	NA	10	40	1	10	5.11	4th
Sycamore (*Acer pseudoplatanus*)	10	50	6	42	7	28	4	32	2	8	1	4	1	10	5.61	9th
Common Ash (*Fraxinus excelsior*)	8	40	9	63	9	36	7	56	8	32	4	16	1	10	5.50	8th
Wild Cherry (*Prunus avium*)	1	5	1	7	3	12	2	16	3	12	7	28	1	10	5.00	3rd
Large leaved lime (*Tilia platyphyllos*)	4	20	2	14	8	32	1	8	4	16	2	8	1	10	4.91	2nd
Horse chestnut (*Aesculus hippocastanum*)	7	35	4	28	5	20	1	8	9	36	8	32	NA	NA	4.68	1st
Small leaved lime (*Tilia Cordata*)	3	15	7	49	1	4	5	40	1	4	9	36	1	10	5.85	10th
Silver birch (*Betula pendula*)	2	10	8	56	6	24	2	16	7	28	3	12	1	10	5.38	6th
Hawthorn May (*Crataegus monogyna*)	9	45	NA	NA	2	8	6	48	5	20	6	24	1	10	5.34	5th
Beech (*Fagus Sylvatica*)	5	25	3	21	4	16	6	48	6	24	5	20	1	10	5.47	7th

Table 6.5: Trees development characteristics. References from: Garden Centre (2015); Abor Day Foundation (2015); British Hardwood Tree Nursery (2015); Pliûra and Heuertz (2003); and, Defra (2007).

Tree species	Max. Height (m)	Max. Diameter (DBH) (cm)	Age to maturity (years)	Max. Age (years)	Early growth pattern: After 10 years of age		After 20 years of age		[b]Growth rate	Roots pattern	Best soil condition	Comments
					Height (m)	Crown (m)	Height (m)	Crown (m)				
Norway Maple (*Acer platanoids*)	15 - 30	150	40 - 50	250	8	4	13	7	Medium 35–60 cm/yr	-	Acidic, alkaline, loamy, moist, sandy, well-drained, wet and clay soils. It has some drought tolerance.	Rapid growth rate till maturity. Tolerates pollution and other urban conditions well.
Sycamore (*Acer pseudoplatanus*)	20 - 35	150	50 - 60	150-250	10	5	15	8	Fast 35-70 cm/yr (Av.=50)	-	All soils. Tolerates salt laden soils.	Rapid growth rate till maturity.
Common Ash (*Fraxinus excelsior*)	24 - 35	160	15-20	≤400	8	5	11	8	Medium 35–60 cm/yr	-	Prefers a deep, moist, cool soil. Tolerates pollution and exposed sites.	-
Wild Cherry (*Prunus avium*)	5 - 20	120	3-7	20 - 90	8	5	14	7	Medium to fast 35–60 cm/yr	Requires deep soil	Prefers light, sandy soil but grows in moist, well-drained soil. Not drought-tolerant.	-
Large leaved lime (*Tilia platyphyllos*)	24 - 28	146 - 200	35	500	8	3	12	8	Medium to fast 35–60 cm/yr	Deep roots	Any well-drained fertile soil. Able to withstand shade and pollution.	-
Horse chestnut (*Aesculus hippocastanum*)	28 - 35	150	20	300	8	4	11	8	Medium 35–60 cm/yr	-	Acidic, loamy, moist, rich, sandy, silty loam, well-drained and clay soils.	Rapid growth rate in the first 10 years
Small leaved lime (*Tilia Cordata*)	24 - 28	146 - 200	35	500	6	4	12	6	-	Deep roots	Good light loam	-
Silver birch (*Betula pendula*)	15 - 25	30 - 150	50	50-100	8	3	18	4	Fast 35-70 cm/yr	-	Rich humus and raw soil of mountainside.	Rapid growth (50-60 cm/yr) in first 20 years.
Hawthorn May (*Crataegus monogyna*)	≤12	30 - 100	-	100-150	4	3	8	5	Slow to medium 30-60 cm/yr (av.=40)	-	-	-
Beech (*Fagus Sylvatica*)	15 - 18	190	18	150-200	4	4	14	7	Slow to medium 30-60 cm/yr	Does not need deep soil	Acidic, loamy, moist, sandy, well-drained and clay soils. Prefers moist, well-drained soil but has some drought tolerance. ([b]**)**	Branches close to the ground

Table 6.6: Predicted future damage potentials of the tree species based on their growth and development characteristics. Notes: RR – Relative rankings of the 'potential for future damage', where 1 represents least potential for damage (or best suitable), and 10 represents highest potential for damage (or least suitable); WR – Weighted rankings, which reflect the proportion of structures available in all sites (relative abundance).

STRUCTURES / TREES	Impermeable pavements (Weight = **5**)		Permeable pavements (Weight = **7**)		Kerbs (Weight = **4**)		Roads (Weight = **8**)		Retaining walls (Weight = **4**)		Footpaths (Weight = **4**)		Buildings (Weight = **10**)		OVERALL RELATIVE TREE RANKING [(Total WR) ÷ (Total RR)]	Best tree ranking
	RR	WR	RR	WR	RR	WR	RR	WR	RR	WR	RR	WR	RR	WR		
Norway Maple (*Acer platanoids*)	8	40	3	21	5	20	3	24	-	-	2	8	-	-	5.38	7th
Sycamore (*Acer pseudoplatanus*)	5	25	5	35	1	4	1	8	-	-	-	-	-	-	6.00	10th
Common Ash (*Fraxinus excelsior*)	7	35	1	7	2	8	2	16	3	12	4	16	-	-	4.95	5th
Wild Cherry (*Prunus avium*)	1	5	-	-	7	28	-	-	-		1	4	-	-	4.11	1st
Large leaved lime (*Tilia platyphyllos*)	10	50	4	28	6	24	-	-	4	16	5	20	-	-	4.76	3rd
Horse chestnut (*Aesculus hippocastanum*)	4	20	2	14	3	12	-	-	2	8	-	-	-	-	4.91	4th
Small leaved lime (*Tilia Cordata*)	9	45	6	42	-	-	-	-	-		-	-	-	-	5.80	9th
Silver birch (*Betula pendula*)	3	15	8	56	8	32	-	-	1	4	-	-	-	-	5.35	6th
Hawthorn May (*Crataegus monogyna*)	6	30	NA	-	-	-	-	-	5	20	-	-	-	-	4.55	2nd
Beech (*Fagus Sylvatica*)	2	10	7	49	4	16	-	-	-	-	3	12	-	-	5.44	8th

6.5.2. Large-leafed Lime (*Tilia platyphyllos*)

Most Large-leafed Limes that cause damage to urban structures (for example, impermeable pavements, retaining walls and footpaths) were very close located to these structures compared to other trees (Figs. 6.8, 6.11, and 6.12). Based on the survey, there was no record of severe to moderate damage by Large-leafed Lime to some structures such as roads and walls. About 20 % of the Large-leafed Limes planted close to permeable pavements caused severe and moderate damage to permeable pavements from an average distance of 0.7 m. The average DBH of the Large-leafed Limes that caused damage were 34 cm. Large-leafed Limes of this diameter were considered as still being in their growing stage (Table 6.5). The older these trees become, the more severe the damage would be. About 55% of the Large-leafed Limes planted close to impermeable pavements caused severe to moderate damage to these structures. These trees were very close located to impermeable pavements as their average distance to the structures was 0 m at an average DBH of 52 cm. About 25 % of Large-leafed Limes planted close to kerbs with an average DBH of 48 cm caused severe to moderate damage to kerb structures. Their average distance to the kerbs was 0.5 m. About 17% of Large-leafed Limes planted close to retaining walls having an average DBH of 46 cm caused severe to moderate damage to these wall structures. Their average distance to the retaining walls was 0.0 m, indicating that they were very close to these structures. Similarly, about 18% of Large-leafed Limes planted close to footpaths having an average DBH of 46 cm caused severe to moderate damage to footpaths. Their average distance to footpaths was also 0.0 m.

When assessing the damage to structures caused by Large-leaved Lime with the relative importance of these structures, Large-leaved Lime came 2nd in terms of choice (Table 6.4). Also, Large-leaved Lime did not rank high in terms of future potential for damage

(Table 6.6). In terms of aesthetics, Large-leaved Lime scored averagely both for spring and autumn assessments (Table 6.7).

Fig. 6.15: Some selected picture of Large lived limes taken from sample sites. All photos were taken by Vincent Uzomah.

6.5.3. Common Ash (*Fraxinus excelsior*)

Common Ash caused severe to moderate damage to permeable pavements, impermeable pavements, kerbs, roads, and retaining walls, but non to walls. Based on the results of this study, it can be inferred that the roots of Common Ash can spread well beyond 2.0 m on the ground surface. About 35% of Common Ash planted close to permeable pavements with an average DBH of 66 cm caused severe to moderate damage to permeable pavements from an average distance of 2.3 m. A Common Ash tree of this DBH is considered to be fully grown (Dobrowolska et. al., 2011).

Common Ash was the farthest tree away that caused damage to permeable pavements. This may be due to its great size. About 70% of Common Ash that were close to impermeable pavements caused severe to moderate damage to these pavement structures. The trees were of an average DBH of 30 cm and were located at an average distance of 0.7 m from the impermeable pavements. Common Ash trees of such DBH are considered to be at a young and developing stage, and are likely to cause more damage to any urban structures in the future. About 50 % of the Common Ash trees that were located closely to kerbs (average distance of 0.9 m) caused severe to moderate damage. Their average DBH was 62 cm. Most of these trees could be considered as mature. About 25 % of Common Ash close to roads with an average DBH of 72 cm caused severe to moderate damage to these road structures. They were located at an average distance of 2.0 m to the roads. About 50% of the Common Ash found close to retaining walls with an average DBH of 53 cm, caused severe to moderate damage to the retaining walls. They were placed at an average distance of 0.3 m from the retaining walls. Common Ash had the highest average distance from the retaining walls amongst other trees that caused damage to retaining walls. The percentage of Common Ash that caused damage to footpaths was the least among damage to other structures. The percentage of the trees that caused damage to footpaths was about 18% with an average DBH of 53 cm and located an average distance of 0.5 m from the footpaths.

Fig. 6.16: Some Common Ash trees at Site 58: Hipley Close, Bredbury, Stockport SK6 1ES and Site 59: Colwell Ave, Stretford, Manchester M32 9HD. All photos were taken by Vincent Uzomah

Common Ash ranked very high (8/10) in terms of potential for damage (Table 6.4) but ranked lower (5/10) in terms of potential for future damage. Most Common Ash trees recorded in this survey were already mature, but reached less than half of their life span when compared with data shown in Table 5. Secondly, none of the Common Ash trees were very close to any structure. Common Ash received average scores (51%) in terms of aesthetics in spring and summer, but very low scores (24%) for autumn.

6.5.4. Sycamore (*Acer pseudoplatanus*)

Sycamore caused damage to structures even if when pland at longer distances to structures such as permeable pavements, impermeable pavements, kerbs and roads. However, there were no recorded damage by Sycamore to footpaths and retaining walls. The average diameter of Sycamore trees that caused damage to structures ranged from 52 cm for permeable pavements to 73 cm for roads and walls. Findings indicated that 6 out of 12 Sycamore trees (50%) with an average DBH of 52 cm caused damage to permeable pavements from an average distance of 0.4 m (Fig. 6.5). Sycamore was the only tree that consistently caused damage from the farthest distance concerning kerbs, impermeable pavements and roads (Figs. 6.8 to 6.10). Sycamore caused the most damage to impermeable pavements from the farthest average distance of 1.2 m with an average DBH of 64 cm (Fig. 6.8).

Because of the potential to cause damage even from a relatively far distance, Sycamore ranked very high (9/10) in the potential for damage (Table 6.4), and also ranked very high (10/10) in the potential for future damage (Table 6.6). On the other hand, Sycamore received high scores for aesthetics regarding spring, summer and autumn seasons (Table 6.7).

Fig. 6.17: Sycamore trees located around Site 66: Alexandra Rd S, Manchester M16 8QJ and Site 70: Monton Green, Manchester M30 9LE. All photos were taken by Vincent Uzomah.

6.5.5. Wild Cherry (*Prunus avium*)

Wild Cherry caused moderate to severe damage to only kerbs and footpaths. Its damage to kerbs was the lowest (1/14 trees) among other trees. Wild Cherries had an average DBH of 62 cm and were located very close (0 m away) to kerbs (Fig. 6.9). The number of wild cherry trees that caused damage to footpaths was also very small (2/14). The DBH was 45 cm and the average distance from the footpaths was 2.5 m.

Concerning future damage, Wild Cherry ranked 3rd (Table 6.4), indicating that it is one of the preferred tree species when considering damage to structures. For predicted future damage potentials, it is ranked 1st (Table 6.6), highlighting that the damage from Wild Cherry are unlikely to get worse compared to other trees. Wild Cherry also scored very high (72%) concerning aesthetics in spring and summer, but low (36%) in autumn.

Most Wild cherry tree roots are exposed to the surface (see Fig. 6.18). Most of them were planted in gardens which may reduce the number of structural damage.

Fig. 6.18: Some Wild Cherry trees within Site 60: Carlisle Close, Little Lever, Bolton BL3 1TF and Site 70: Monton Green, Manchester M30 9LE. All photos were taken by Vincent Uzomah.

6.5.6. Horse chestnut (*Aesculus hippocastanum*)

Horse Chestnuts cause moderate to severe damage to permeable pavements, impermeable pavements, kerbs and retaining walls, but none to roads, footpaths and walls.

About 32% of Horse Chestnuts caused moderate to severe damage to these structures. Most Horse Chestnuts that caused damage were of mature in size with an average DBH ranging from 51 to 71 cm (Figs. 6.5 and 6.8 to 6.13).

Horse Chestnut was ranked as the 2^{nd} (2/10) best tree with regards to damage to structures, and ranked 4^{th} best in potential for future damage, because most of the assessed trees were already mature. However, Horse Chestnut leaves generally cause a lot of litter on streets during autumn. In terms of aesthetics, Horse Chestnuts scored very high (80%) in spring and summer, but very low (39%) in autumn (Table 6.7), indicating that horse chest nut attracts very high appeal in summer due to its high density green leaves. Some images showing the impact of horse chestnuts on some structures are shown in Fig. 6.19.

However, horse chestnuts litter roads with a lot of conkers which increases the cost of cleaning the roads. But the conkers increases the biodiversity of the area where horse chestnuts are found as it is food for many animals.

Fig. 6.19: Pictures showing some interaction of Horse chestnuts with their surrounding structures around Sites: 66 - Alexandra Rd, Manchester M16 8QJ; 25 - Barcicroft road, M19 1WF; and 3 Clivia Grove, M7 2AE. All photos were taken by Vincent Uzomah.

6.5.7. Small leaved Lime (*Tilia Cordata*)

Small-leaved Lime caused moderate to severe damage to permeable pavements, impermeable pavements and walls, and none to kerbs, roads, retaining walls and footpaths (Figs. 6.5 and 6.8 to 6.13). Distances of Small-leaved Limes to structures were generally within an average distance of 0 m (as for impermeable pavements) to 0.7 m (as for permeable pavements). Most Small-leaved Limes that caused damage could be classed as still being very young, since their average DBH were between 26 to 38 cm, compared with that of 146 to 200 cm for a mature Small-leaved Lime trees (Figs. 6.5, 6.8 and 6.13, and Table 6.5).

Small-leaved Lime caused damage at young ages with smaller DBH and therefore was ranked as a tree with a high potential to cause damage both in the presence and in the future. It was not among the trees assessed for public acceptance, but would likely have scored similar to Large-leaved Lime.

6.5.8. Silver Birch (*Betula pendula*)

Silver birch caused moderate to severe damage to permeable pavements, kerbs, walls and retaining walls, but none to impermeable pavements, roads and footpaths. The DBH for silver birches that caused damage varied widely from 20 cm for those near permeable pavements, 45 cm for those near kerbs, 73 cm for those near walls, and 125 cm for those near the retaining walls. Most silver birches that caused damage were very close to the structures they damaged, except for those close to walls, which were at an average of 0.9 m away. Due to silver birch being able to cause damage even at smaller DBH, it ranked very high in potential for structural damage both at present and for future (Tables 6.4 and 6.6). Fig. 6.20 shows some pictures of silver birch in some of the assessed sites.

Fig. 6.20: Silver birch. Photos were taken by Vincent Uzomah.

6.5.9. Hawthorn may (*Crataegus monogyna*)

Hawthorn May caused moderate to severe damage to only impermeable pavements and retaining walls at an average DBH of 25 cm and 20 cm respectively (see Figures 6.5 and 6.8 to 6.13), indicating that they were still relatively small trees. However, 2 out of 4 Hawthorn mays caused moderate to severe damage to impermeable pavements from an average distance of 1 m, while 1 out of 3 caused damage to retaining walls from an average distance of 0 m (Figures 6.8 and 6.11).

Hawthorn may ranked 5th in preference in terms of potential for damage, likely because, though it featured close to most structures but damaged only two (Table 6.4). However, it ranked 2nd in terms of preference against future damage (Table 6.6) likely because, the size may not increase significantly much in future due to their natural size (see Table 6.5). Hawthorn may was also scored relatively high (68%) in aesthetics and public acceptance. Pictures of Hawthorn May from some of the assessed sites are shown in Fig. 6.21.

Fig. 6.21: Some Hawthorn May trees from the assessed sites. All photos were taken by Vincent Uzomah.

6.5.10. Beech (*Fagus Sylvatica*)

Beech trees caused moderate and severe damage to permeable pavements, impermeable pavements, kerbs and footpaths, but non to roads, walls and retaining walls. The average DBH of most beech trees that caused damage were relatively large, ranging from 68 to 93 cm (Figures 6.5, 6.8, 6.9 and 6.12), indicating that they are already large and matured (see Table 6.5). In all cases of damage to structures, Beech trees appeared to be the largest sized trees occurring as they have the largest DBH wherever they featured (Figures 6.5, 6.8, 6.9 and 6.12). Beech tree has a relatively high score for aesthetics and public acceptance for spring/summer seasons, and the highest score for autumn seasons.

6.6. DISCUSSION ON PUBLIC PERCEPTIONS AND AESTHETICS FOR THE TREES OF MOST CONCERNS.

The tree that is much appreciated in all seasons is the tree that scores high in both seasons, thereby making the ‘Difference column’ very low (Table 6.7). The tree that scored the in highest public acceptance in spring season is the Norway Maple (*Acer platanoides*) (Table 6.7). This probably explains why it is the most populous tree in Greater Manchester as shown from this study. However it scored relatively low for the autumn season. Similarly, Common Horse Chestnut (*Aesculus hippocastanum*) scored high in public acceptance in spring but low in autumn. On the other hand, Sycamore (*Acer pseudoplatanus*) scored very high in public acceptance both in spring and autumn seasons, making it much accepted in all seasons.

Table 6.7: Result of the public acceptance assessment of some selected predominant trees in Greater Manchester.

Tree Species	Average Percentage scores for Spring/Summer tree pictures		Percentage scores for Autumn tree pictures		All-round season average (%)
	Tree ID No.	Average Score	Tree ID No.	Average Score	
Norway Maple *(Acer platanoide)*	16	83	19	43	63
Sycamore *(Acer pseudoplatanus)*	2	75	17	66	71
Common ash *(Fraxinus excelsior)*	18	51	9	24	38
Wild cherry (*Prunus avium*)	20	72	13	36	54
Large-leaved lime *(Tilia platyphyllos)*	1	63	23	49	56
Horse chestnut (*Aesculus hippocastanum*)	22	80	24	39	60
Common Lime *(Tilia × europaea)*	14	56	6	32	44
London Plane *(Platanus × acerifolia)*	5	43	11	31	37
Common Hawthorn *(Crataegus monogyna)*	12	68	4	37	53
Common Beech *(Fagus Sylvatica)*	8	69	21	60	65
Weeping Willow *(Salix babylonica)*	7	57	3	23	40
Common Holly *(Ilex spp.)*	10	48	15	46	47

6.7. Multiple Regression Analysis

Multiple Regression Analysis was carried out using SPSS Statistics to predict the relationship between the dependent variable - the severity of damage by trees to urban structures, against the independent variables – the average distance of trees from structures, diameter of trees at breast height (DBH), tree height, and tree crown spread. There predicted equations are given below.

For Norway maples (*Acer platanoide)* (R = 0.594):

$$S = -0.403 - 0.216D + 0.032B + 0.004H + 0.153C \qquad Eqn.\ 6.1$$

For Sycamore *(Acer pseudoplatanus)* (R = 0.452):

$$S = -0.329 - 0.014D + 0.021B - 0.118H + 0.235C \qquad Eqn.\ 6.2$$

For Common ash *(Fraxinus excelsior)* (R = 0.531):

$$S = -0.466 - 0.051D + 0.015B + 0.114H - 0.018C \qquad Eqn.\ 6.3$$

For Horse chestnut (*Aesculus hippocastanum*) (R = 0.562):

$$S = 3.982 - 1.077D - 0.017B + 0.190H - 0.228C \qquad Eqn.\ 6.4$$

For Large leaved lime *(Tilia platyphyllos)* (R = 0.641):

$$S = 2.283 - 0.610D + 0.013B + 0.091H - 0.169C \qquad Eqn.\ 6.5$$

For Small leaved lime (*Tilia Cordata*) (R = 0.587):

$$S = -0.105 - 0.201D - 0.027B + 0.173H + 0.089C \qquad Eqn.\ 6.6$$

Where:

$S = Severity\ of\ damage\ in\ numbers\ between\ 0\ to\ 5$
$: 0 - No\ damage; 1 - Slight\ damage \ldots 5 - Very\ severe\ damage$

$D = Average\ Distance\ of\ the\ tree\ from\ structures\ in\ m$

$B - Diameter\ of\ tree\ at\ breast\ heigh\ (DBH)\ in\ cm$

$C = Tree\ crown\ spread\ in\ m$

$H = Tree\ height\ in\ m$

The expected Severity of damage, S varies from 0 to 5, where 0 means no damage expected; 1 indicates minor damage; 2 predicts slightly moderate damage; 3 moderate damage; 4 predicts severe damage; and 5 predicts very severe damage. However, the above interpretation is a guide. Therefore, the interpretation of S when it is, for example, 1.5 can either be a minor damage or a slight moderate damage.

Multiple correlation coefficient, R, is considered to be one measure of the quality of the prediction of the dependent variable. The R for Norway maple in the Eqn. 6.1 is 0.594, indicating a fairly good level of prediction. However, $R^2 = 0.353$, indicating that the independent variables (D, B, C and H) explain only 35.5% of the variability of the dependent variable (the severity of the damage), which is rather low. This pattern of R^2 is similar in all trees studied, and could be because of so many other factors that could also affect the likelihood of a Norway maple tree causing damage to structures.

The R for Sycamore in Eqn. 6.2 is 0.452, indicating a low level of prediction. R for Common ash, Horse chestnut and Small leaved lime in Eqns. 6.3, 6.4 and 6.6 respectively, indicate fairly good levels of prediction. R for Large leaved lime, 0.641, indicates a good level of prediction.

6.8. Chapter Summary

Based on the survey, the percentage of tree species occurence in Greater Manchester were Norway Maple (*Acer platanoides*), 13.6%; Sycamore (*Acer pseudoplatanus*) 9.3%; Common Ash (*Fraxinus excelsior*), 8.2%; Wild Cherry (*Prunus avium*), 7.5%; Large-leaved

Lime (*Tilia platyphylos*) 7.1%; Horse Chestnut (*Aesculus hippocastanum*), 6.9%; Small-leaved Lime (*Tilia cordata*), 5.2%; Silver Birch (*Betula pendula*), 4.7%; Common Hawthorn (*Crataegus monogyna*), 3.5%; and Beech (*Fagus sylvatica*), 2.2%, etc.

The most structural damage by tree occurred to impermeable pavements (44%) followed by permeable pavements (22%), kerbs (19%), retaining walls (5%), foothpath (4%), roads (3%), walls (3%) building (0%).

The best tree combination for **permeable pavements** is Wild Cherry (*Prunus avium*), while the least recommended combinations are: Common Ash (*Fraxinus excelsior*) and Small-leaved Lime (*Tilia cordata*). The best tree combinations for **impermeable pavements** are: Wild Cherry (*Prunus avium*) and Silver Birch (*Betula pendula*), while the least recommended combinations are with: Sycamore (*Acer pseudoplatanus*), Horse Chestnut (*Aesculus hippocastanum*), Hawthon May (*Crataegus monogyna*) and Common Ash (*Fraxinus excelsior*). The best tree combinations recommended for **kerbs** are: Wild Cherry (*Prunus avium*), Small-lived Lime (*Tilia cordata*) and Beech (*Fagus sylvatica*), while the worst combinations are: Common Ash (*Fraxinus excelsior*), Norway Maple (*Acer platanoides*) and Large-leaved Lime (*Tilia platyphylos).* The best trees that could be recommended to be planted near a **road** are: Wild Cherry (*Prunus avium*), Large-leaved Lime (*Tilia platyphylos*) and Horse Chestnuts (*Aesculus hippocastanum*), while the least recommended tree near the roads is Common Ash (*Fraxinus excelsior*). However, the problem with Horse Chestnut is the littering around of the seeds on the roads. Therefore, consideration should be given about the adequate distance from the road. The best trees that could be recommended near **retaining walls** are: Small leaved-lime (*Tilia cordata*), Sycamore (*Acer pseudoplatanus*) and Large-lived Lime (*Tilia platyphylos*), while the least recommended are: Horse Chestnut (*Aesculus hippocastanum*) and Common Ash (*Fraxinus* *excelsior*). The best tree recommended for footpath is Sycamore (*Acer pseudoplatanus*) while the least recommended is Beech (*Fagus sylvatica*).

CHAPTER 7

CONCLUSIONS AND FUTHER RESEARCH

7.1. CONCLUSIONS

A rapid estimation methodology for retrofitting of SUDS was successfully introduced to reduce the currently high level of subjectivity in practice. Retrofitting of SUDS is possible for a high number of sites within a densely built-up area such as Greater Manchester. Generic ecosystem service variables suitable for SUDS were determined, and broadly categorised under the four established categories of supporting, regulating, provisioning and cultural. Due to the high density of built-up areas, the overall ecosystem service scores were relatively low. This rapid decision support methodology based on novel ecosystem service variables was also used to assess the potential for retrofitting of SUDS and combined permeable pavements and tree systems in the densely populated areas.

The suitability of sites for SUDS retrofitting was assessed based on traditional 'community and environment' variables and the new ecosystem service variables. The old traditional approach favours infiltration trenches, soakaways and belowground storage systems. In comparison, the new approach promotes permeable pavement systems regardless of the professional perspective. All sites were suitable for the retrofitting of SUDS when the traditional assessment based on 'community and environment' variables was carried out. In comparison, the ecosystem services approach shows that nearly half of the sites visited are valued as having a relatively low ecosystem services potential, making them of restricted use for retrofitting of most SUDS techniques. This finding can be used to prioritise sites for SUDS retrofitting, which is particularly important during difficult financial times.

A weighting system for the variables as a function of the SUDS technique was successfully introduced to reduce the impact of what may be perceived as less relevant ecosystem service variables. The introduced weighting system was able to reduce a professional bias considering that, for example, an engineer would have a different weighting system (possibly biased towards structural integrity of the pavement) than an ecologist (perhaps greater emphasize on habitat and biodiversity), sociologist (more oriented to assess cultural services) and geographer (greater awareness of spatial variability).

The introduction of a transparent and justified weighting system as a reflection ~~function~~ of different professional bias led to the preferred selection of some SUDS techniques by several professions.

Retrofitting of combined permeable pavement and tree systems is generally possible for a high number of sites within a densely build-up area such as Greater Manchester. However, the case study area was dominated by only a few tree species (Norway Maple, Sycamore, Common Lime, etc.). This finding is similar to previous results for other conurbations. However, a few tree species are unsuitable for the successful operation of permeable pavement systems due to factors such as unsuitable fruits (Horse Chestnut) and destructive root system (some Wild cherry, Poplar species and Weeping Willow).

Analysis of urban structural damage with respect to tree characteristics such as species, distance from structures and DBH were carried out. The damage to structures by trees did not follow any particular pattern. Factors such as distance of tree from structure, tree age, soil type, tree species, type of underlying foundation material, extent of the compaction of the underlying materials, as well as availability of oxygen and moisture regimes in the soil affect the degree of damage to structures by trees. Impermeable pavements were subject to the highest number of damage from trees (44%), followed by permeable pavements and kerbs (22% and 19%, respectively). Other structural damage to roads, retaining walls and houses ranged from 0 to 5%.

Trees planted close to impermeable pavements caused more damage to the structure compared to those planted close to permeable pavements under the same conditions. This confirms previous observations indicating that impermeable pavements trap moisture at the underside of their surface, which would have otherwise evaporated in the case of permeable pavements, and thereby become attractions for tree roots.

The more compacted underlying materials are, the greater is the likelihood that tree roots will spread close to the surface, and thereby damaging roads and SUDS structures. Roots of trees planted in not compacted underlying soil media, for example, in parks, fields and footpaths did not spread along the ground surface, but went deeper into the soil causing little or no damage to these structures.

Therefore, impermeable pavements should be replaced with permeable pavements. This will reduce maintenance cost of road repairs from tree damage. Permeable pavements improve the water availability in the root zones of urban trees and they, therefore, improve the overall tree heath and soil properties. This will therefore increase the benefits derived from urban trees.

Wild cherry, large leaved lime, horse chestnut and hawthorn may are the best recommended trees for use alongside roads and SUDS structures as they have least potential to damage structures. However, horse chestnuts produce lots of litters with their conkers. The analyses of tree aesthetics/public acceptance were carried out using tree pictures taken at the National Arboretum at Westonbirt. The results of the aesthetic/public acceptance showed that the sycamore was the most aesthetic tree all-round the year.

This research also aims at predicting some prevalent mature trees that could be combined with the retrofitting of sustainable drainage systems. In line with this, regression analysis was used to predict the likelihood of some urban structures to be damaged by specific mature trees within their vicinity. Equations of severity of damage for specific trees were developed. The severity of damage equation for Large leaved lime indicated a good level of prediction. That for Common ash, Horse chestnut and Small leaved lime indicated fairly good levels of prediction. It is therefore possible to predict the extent of structural damage (if any) by specific mature trees by determining its distance from structures, height, diameter at breast height (DBH), and crown spread.

7.2. FURTHER RESEARCH

More research is recommended to develop the 'ecosystem service' assessment approach further into a numerical model. Additional urban but also rural case studies with a larger number of sites could be assessed to test the robustness of the new approach and to subsequently refine it. The tool should also be tested at a relatively small scale such as a neighbourhood or housing development in different cities, towns and villages. This would allow for the assessment of variability as a function of scale and local peculiarities for individual SUDS techniques.

Larger cohorts of experts and non-experts could be used to refine the estimation methodology and weighting systems. Specific weighting systems for the ecosystem service variables as a function of different climatic regions and cultures could be introduced.

Collection of more data on tree characteristics such as diameter at breast at height (1.5 m), tree height, crown spread, tree species, surrounding structures, structural damage caused by the tree, severity of the damage, distance of the tree from the structure, etc., is recommended so as to enable a clear expression of a relationship between tree characteristics and their potentials to cause structural damage.

There is need for further assessment of the public acceptance and values for trees predominantly found in Greater Manchester. This will help to give a thorough evaluation of the benefits of urban trees.

There could also be an opportunity for developing a computer programme that will automatically use the field data input to generate the best suitable SUDS techniques for retrofitting.

Further research is also recommended on the influence of compacted soil layers on the spread and performance of urban tree roots.

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APPENDIX

APPENDIX A: THE SUDS DECISION SUPPORT TOOL

APPENDIX B: THE QUESTIONNAIRE USED IN ASSESSING DIFFERENT PROFESSIONS' PERSPECTIVES (THE SURVEY)

APPENDIX C: THE SITE LOCATION PROFILES

APPENDIX D: THE SITE LOCATION POINTS AND BOUNDARIES

APPENDIX E: SOME OF THE PUBLICATIONS FROM THE RESEARCH

APPENDIX F: THE PRINCIPAL COMPONENT ANALYSIS